Geophysical Investigation of Asteroids by Dawn Spacecraft

Caltech Planetary Seminar

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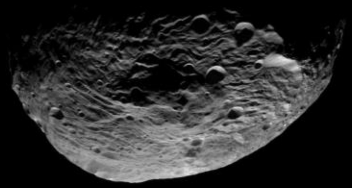
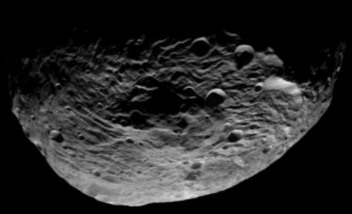


Goal of the talk:

- Explain how the internal structures of Vesta and Ceres evolved by looking at the present-day topography and gravity measured by Dawn



How do we use shape data to study interiors?

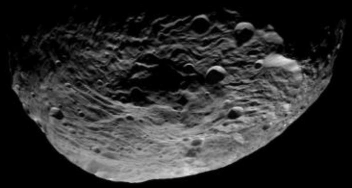
- Hydrostatic equilibrium

- Isostatic compensation

- Viscous relaxation

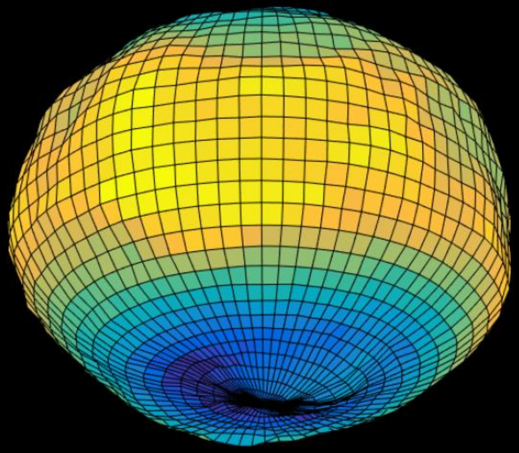
- Shape model is required for computing gravity anomalies
- Topographic roughness
- Local geomorphology

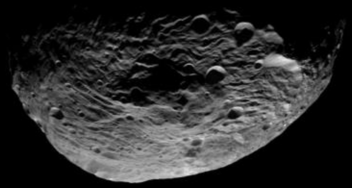
beyond this talk



Shape models

- **Geographic grid**





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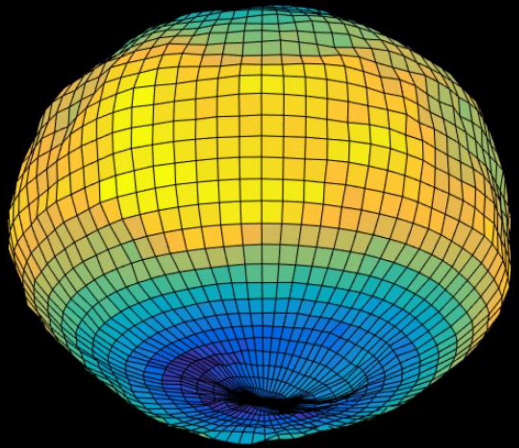

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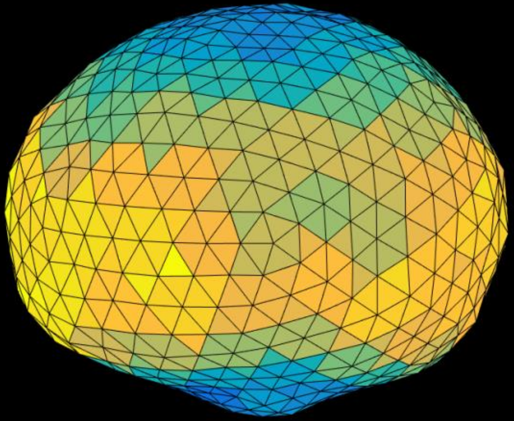
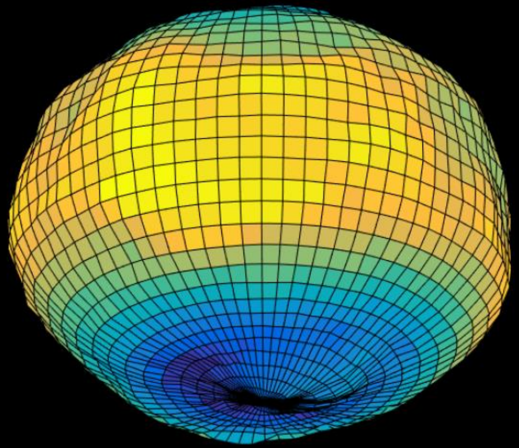


- Polyhedral model

Shape models



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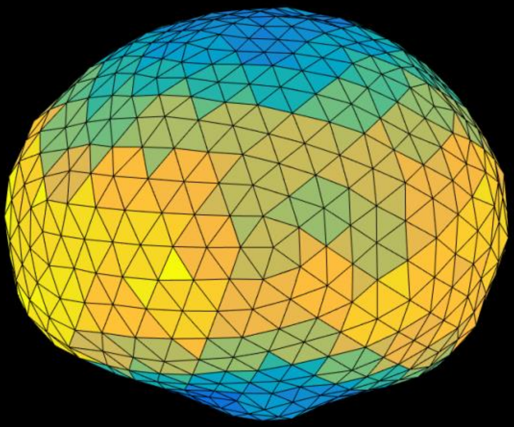

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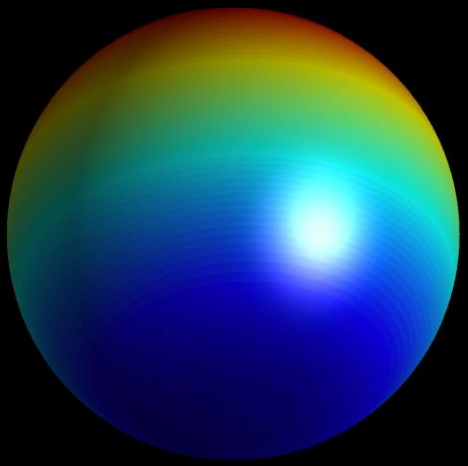


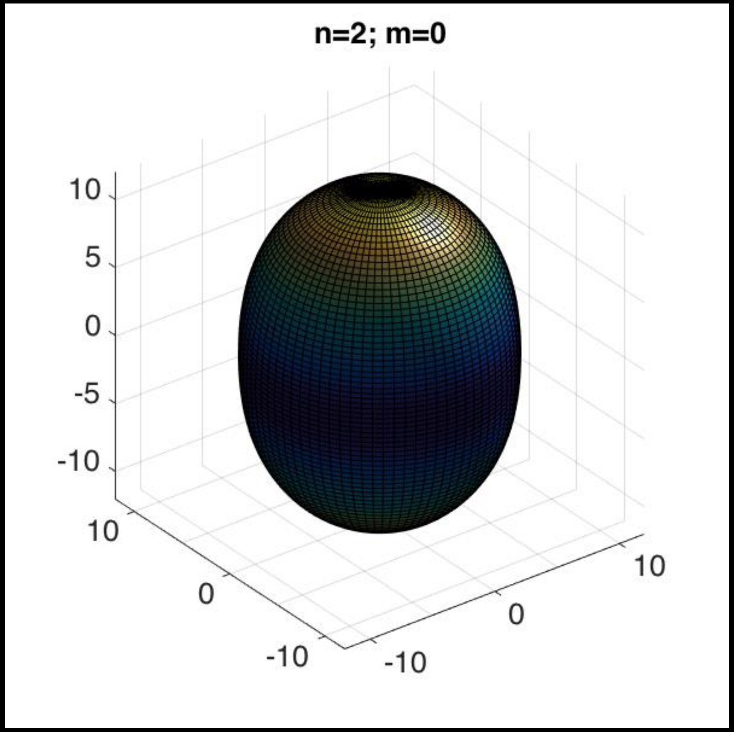
- Spherical harmonic expansion
  - set of orthogonal functions on a sphere

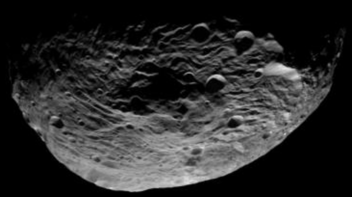
Gravity models

- **Spherical harmonics**

$$U(r,\varphi,\lambda) = \frac{GM}{r}\left[1 + \sum_{n=2}^{\infty}\sum_{m=0}^{n}\left(\frac{R_0}{r}\right)^n \left(C_{nm}\cos(m\lambda) + S_{nm}\sin(m\lambda)\right)P_{nm}(\sin\varphi)\right]$$

U **– gravitational potential**
φ **– latitude**
λ **– longitude**
r **– radial distance**
n **– degree**
m **– order**





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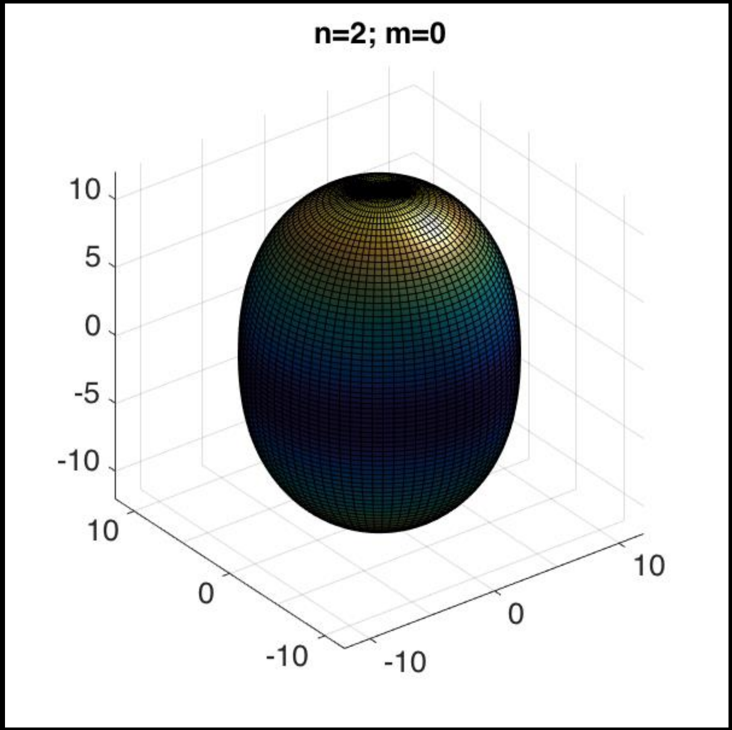


- **Ellipsoidal harmonics**
- **Mascons**

Gravity and topography in spherical harmonics

- **Shape radius vector**

$$r(\phi,\lambda) = R_0 \left[\sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(A_{nm}\cos(m\lambda) + B_{nm}\sin(m\lambda) \right) P_{nm}(\sin\phi) \right]$$

- **Gravitational potential**

$$U(r,\phi,\lambda) = \frac{GM}{R}\left[1 + \sum_{n=2}^{\infty} \sum_{m=0}^{n} \left(\frac{R_0}{r}\right)^{n} \left(C_{nm}\cos(m\lambda) + S_{nm}\sin(m\lambda) \right) P_{nm}(\sin\phi) \right]$$

- **Power Spectral Density**

$$S_n^{gg} = \sum_{m=0}^{n} \frac{C_{nm}^2 + S_{nm}^2}{2n+1}$$

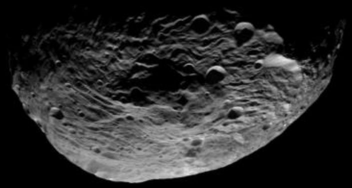
gravity

$$S_n^{tt} = \sum_{m=0}^{n} \frac{A_{nm}^2 + B_{nm}^2}{2n+1}$$

topography

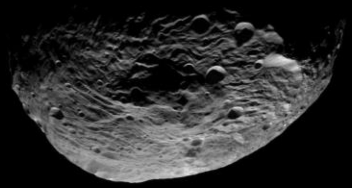
$$S_n^{gt} = \sum_{m=0}^{n} \frac{A_{nm}C_{nm} + B_{nm}S_{nm}}{2n+1}$$

gravity-topography cross power



Hydrostatic equilibrium

- In hydrostatic equilibrium
  - Surfaces of constant density, pressure and potential coincide
  - No shear stresses



Hydrostatic equilibrium

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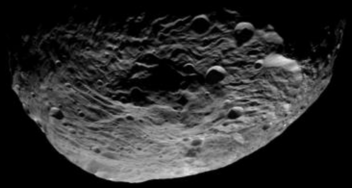
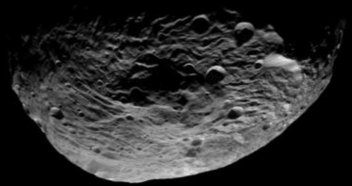


Hydrostatic equilibrium

- **In hydrostatic equilibrium**

$\rho = \rho(r)$, ω

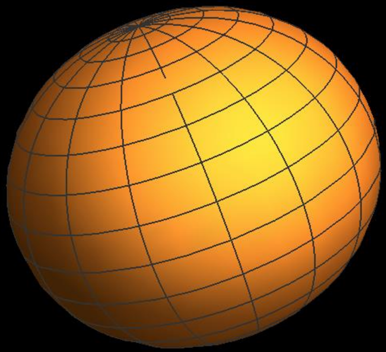


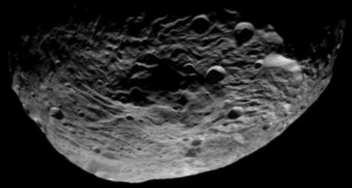
Hydrostatic equilibrium

- **In hydrostatic equilibrium**

easy

$\boldsymbol{\rho = \rho(r), \omega}$





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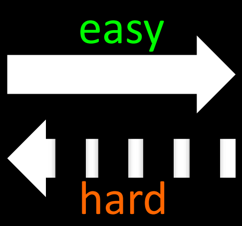
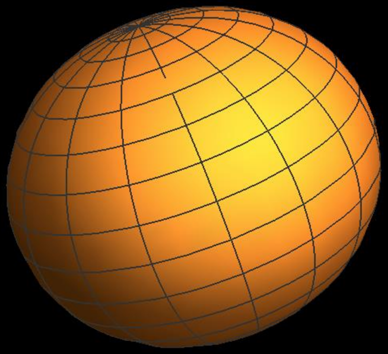
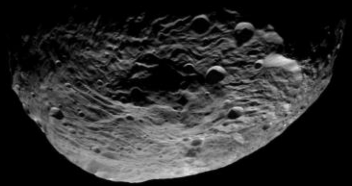






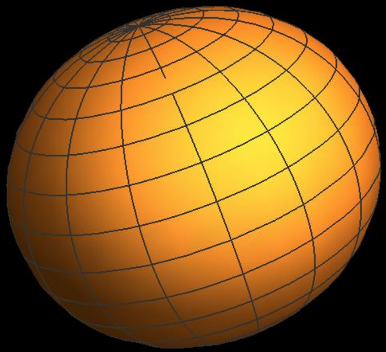
Hydrostatic equilibrium

- **In** hydrostatic equilibrium

$\rho = \rho(r), \omega$

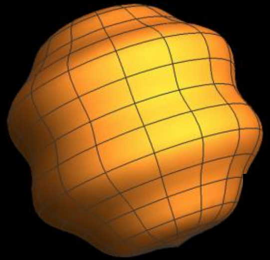
easy

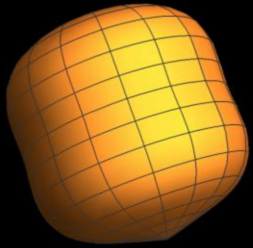
hard

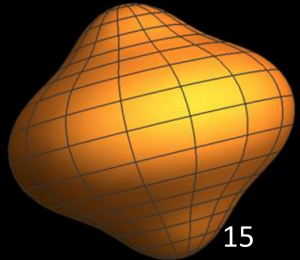


- **Not in** hydrostatic equilibrium

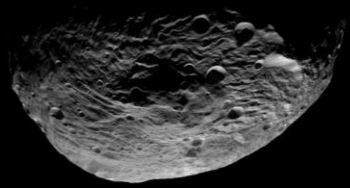
$\rho = \rho(r), \omega$



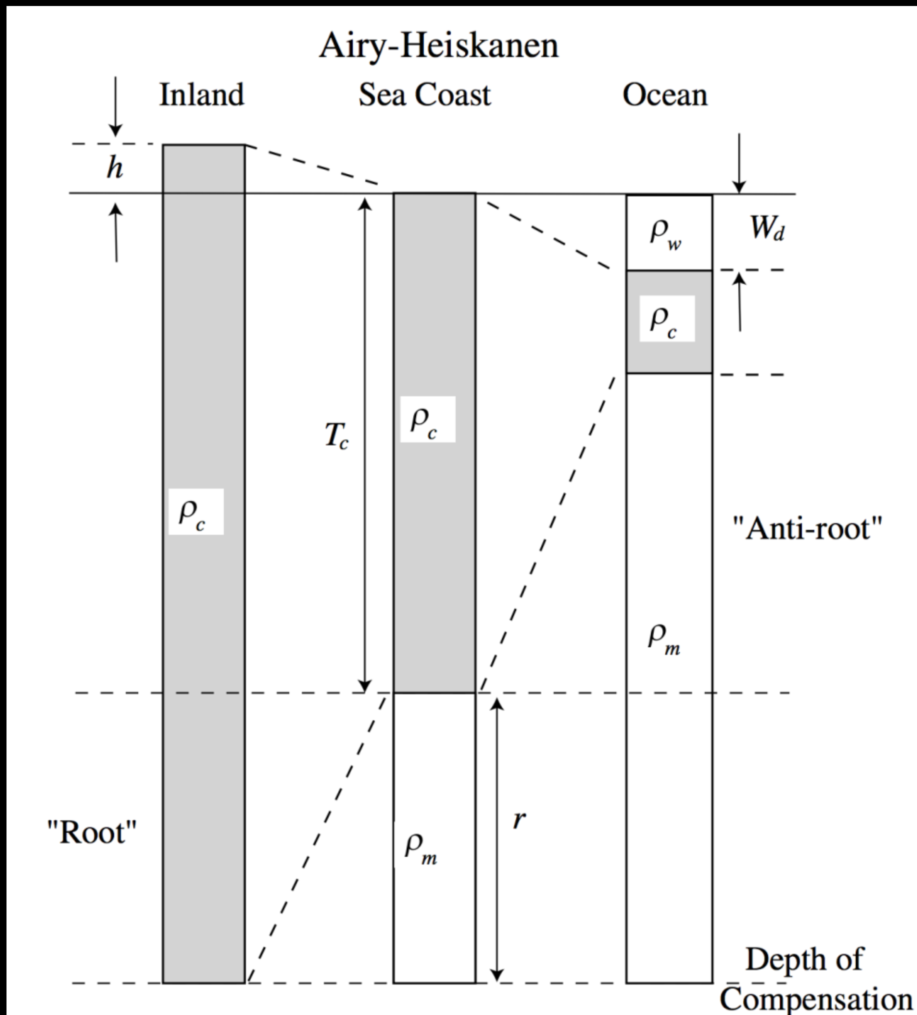




very hard



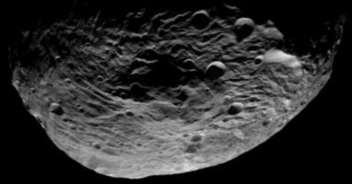
Isostasy



Watts, 2001

Isostatic equilibrium:

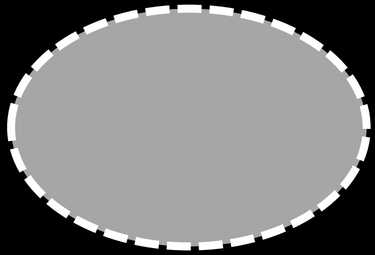
- **Equal weight of crustal columns at the depth of compensation**
- **Deviatoric stresses within the isostatically compensated layer are minimized**

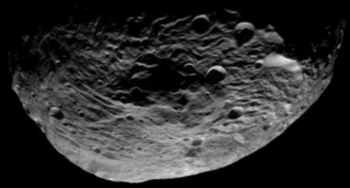


Gravity anomalies

- **Free-air anomaly** $\sigma_{FA} = \sigma_{obs} - \sigma_{model}$

σ_{model} = **gravity of hydrostatic figure**





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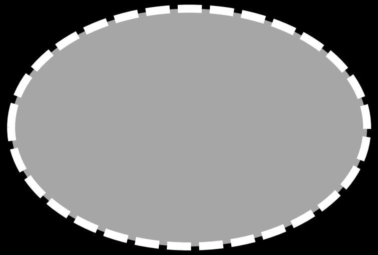
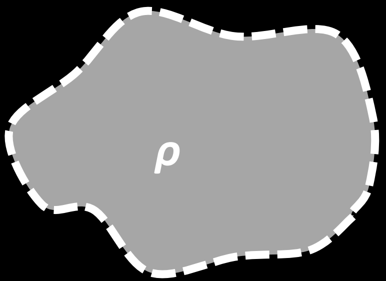
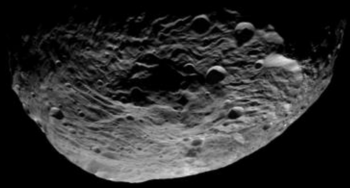


- **Bouguer anomaly** $\sigma_{BA} = \sigma_{obs} - \sigma_{model}$

σ_{model} = **gravity of shape assuming ρ**





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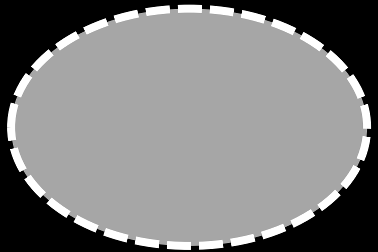

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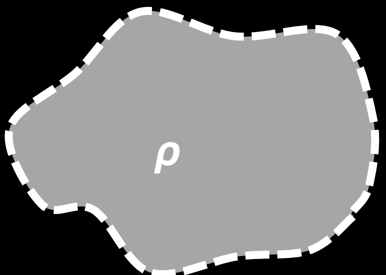
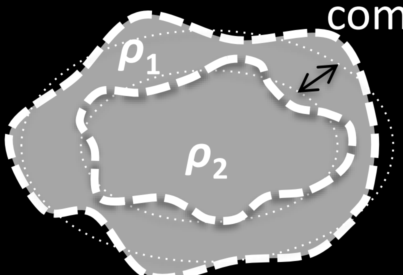


- **Isostatic anomaly** $\sigma_{IA} = \sigma_{obs} - \sigma_{model}$

h – depth of compensation

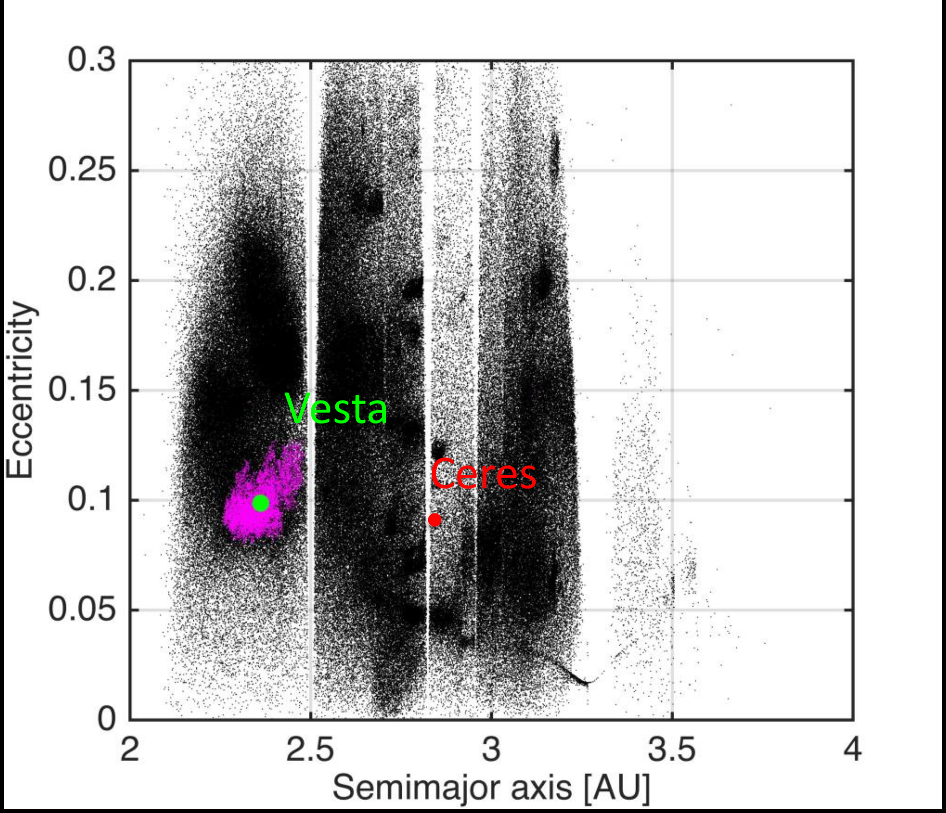
σ_{model} = **gravity assuming isostasy for ρ_1, ρ_2, h**

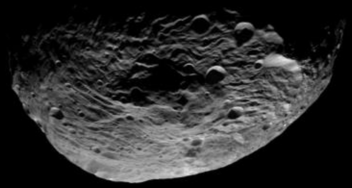


Why Ceres?

- Largest body in the asteroid belt
- Low density implies high volatile content
- Conditions for subsurface ocean
- Much easier to reach than other ocean worlds

Ceres location in the asteroid belt





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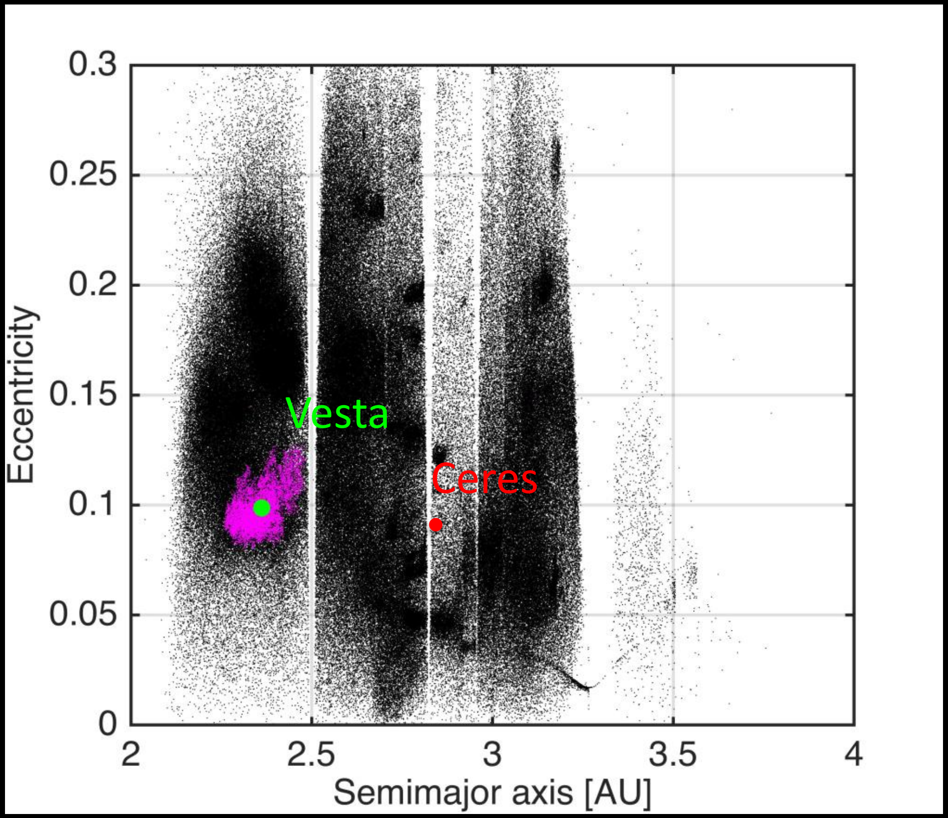
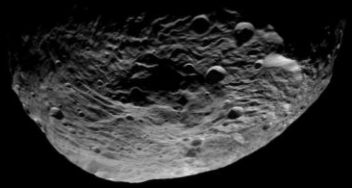
- Largest body in the asteroid belt
- Low density implies high volatile content
- Conditions for subsurface ocean
- Much easier to reach than other ocean worlds
- Major unexplored object in the asteroid belt

Ceres location in the asteroid belt

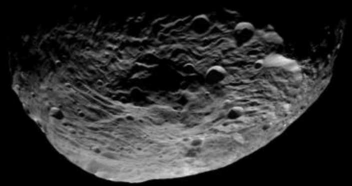




What did we know before Dawn

- **Castillo-Rogez and McCord 2010**

  Ceres accreted as a mixture of ice and rock just a few My after the condensation of Calcium Aluminum-rich Inclusions (CAIs), and later differentiated into a water mantle and a mostly anhydrous silicate core.



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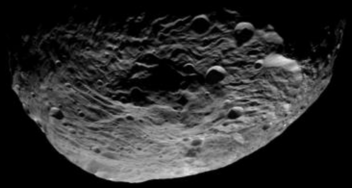
  Ceres formed relatively late from planetesimals consisting of hydrated silicates.



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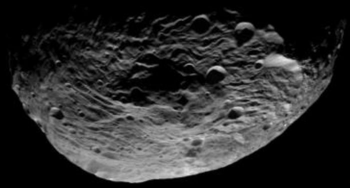
- **Zolotov 2009**

  Ceres formed relatively late from planetesimals consisting of hydrated silicates.

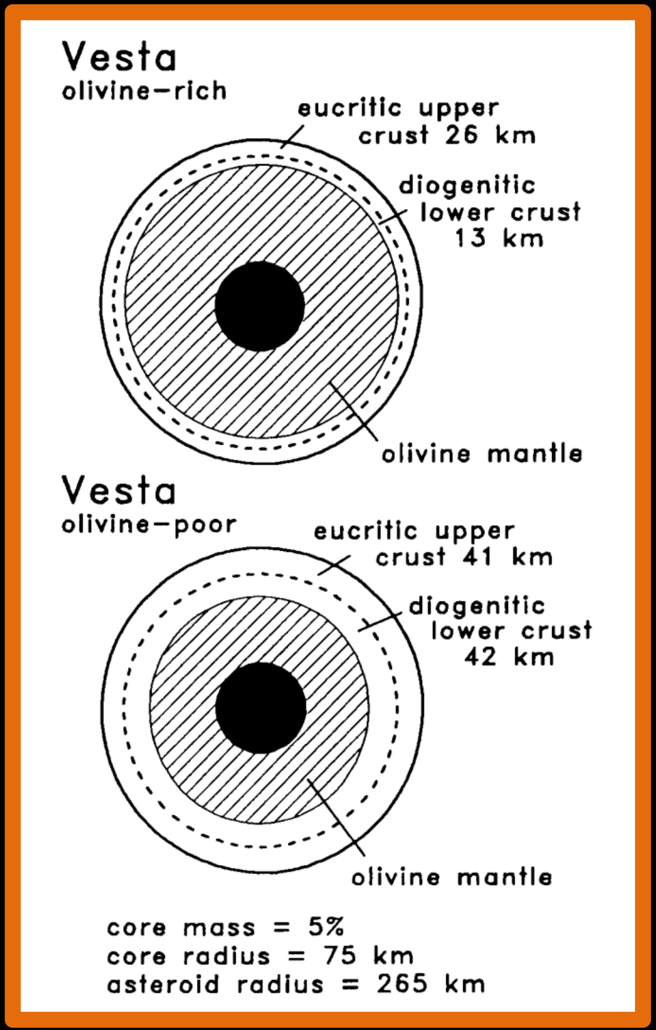
- **Bland 2013**

  If Ceres *does* contain a water ice layer, its warm diurnally-averaged surface temperature ensures extensive viscous relaxation of even small impact craters especially near equator



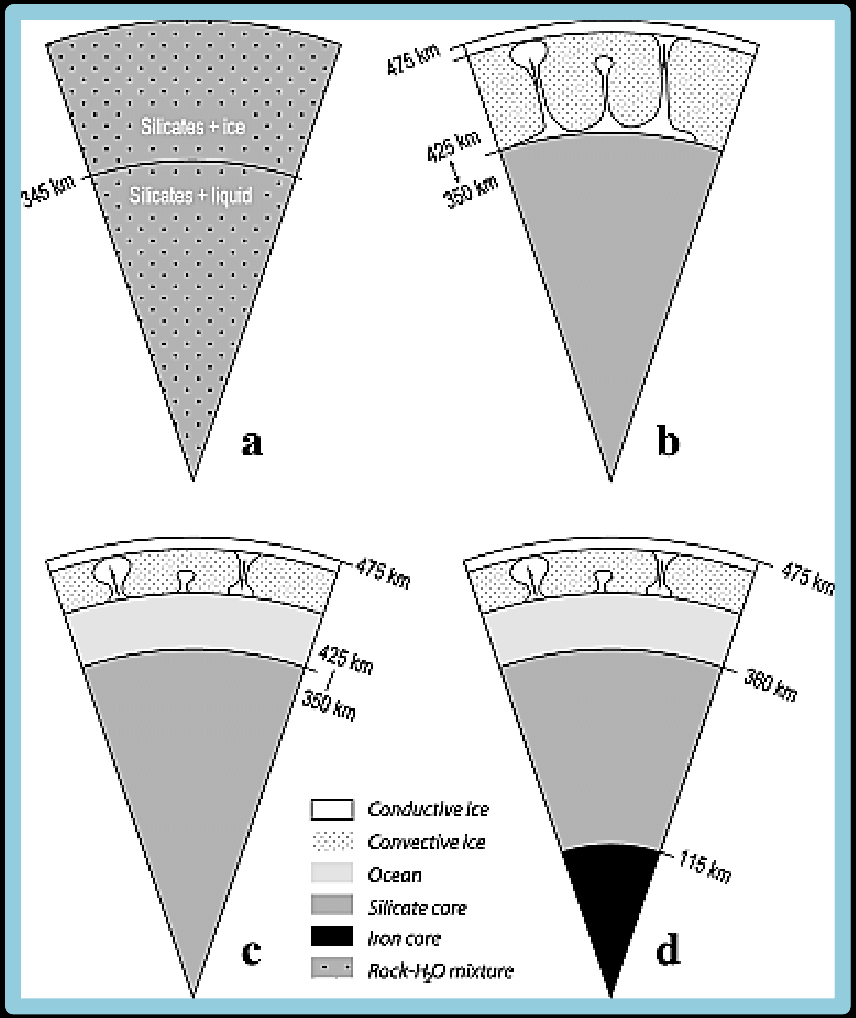
What did we know before Dawn?

Vesta

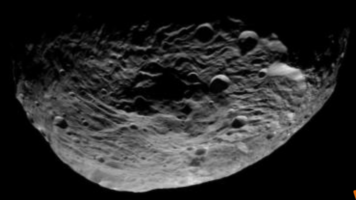


Ruzicka et al., 1997

Ceres



McCord and Sotin, 2005



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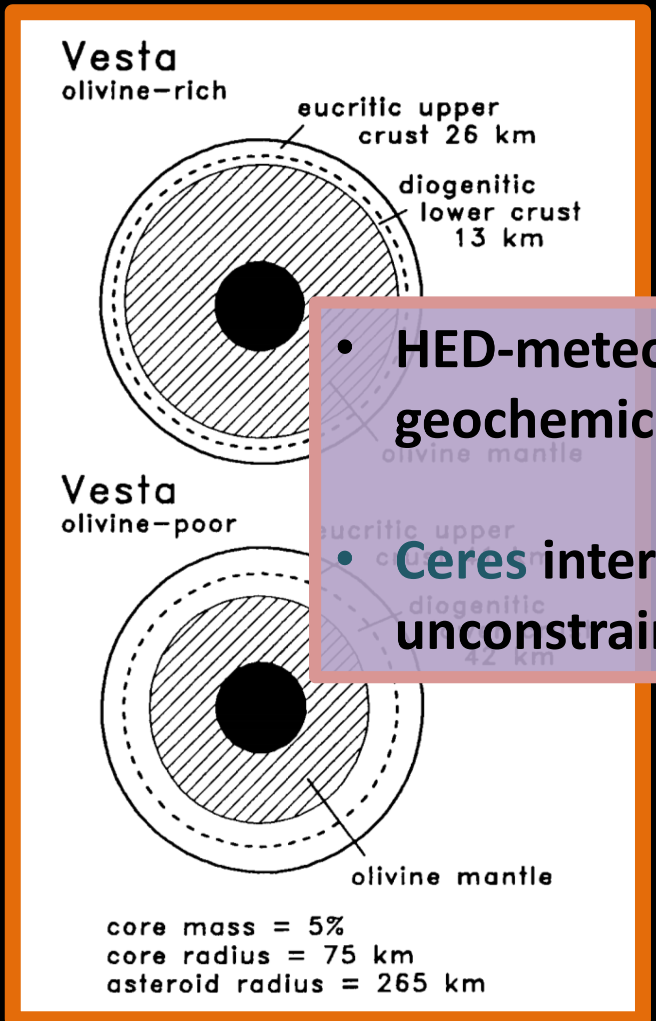
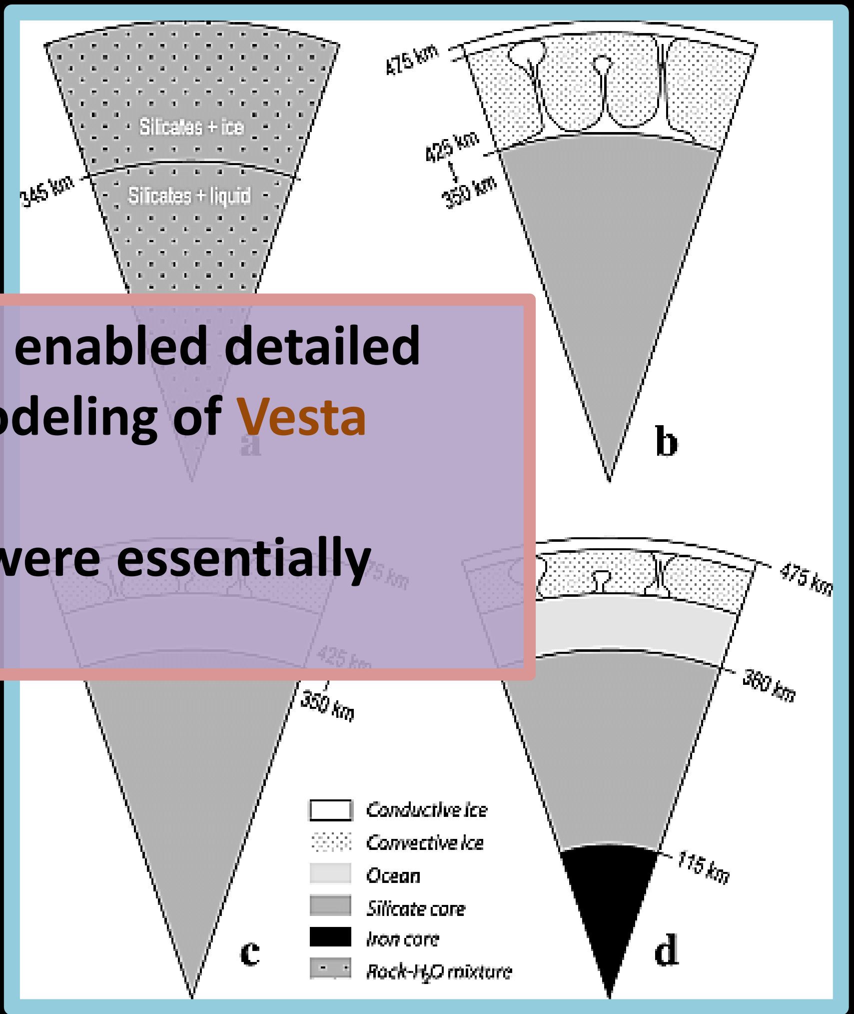


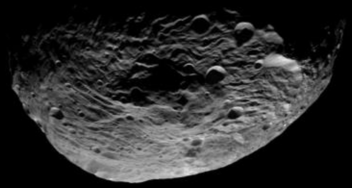
Ruzicka et al., 1997

Ceres



McCord and Sotin, 2005

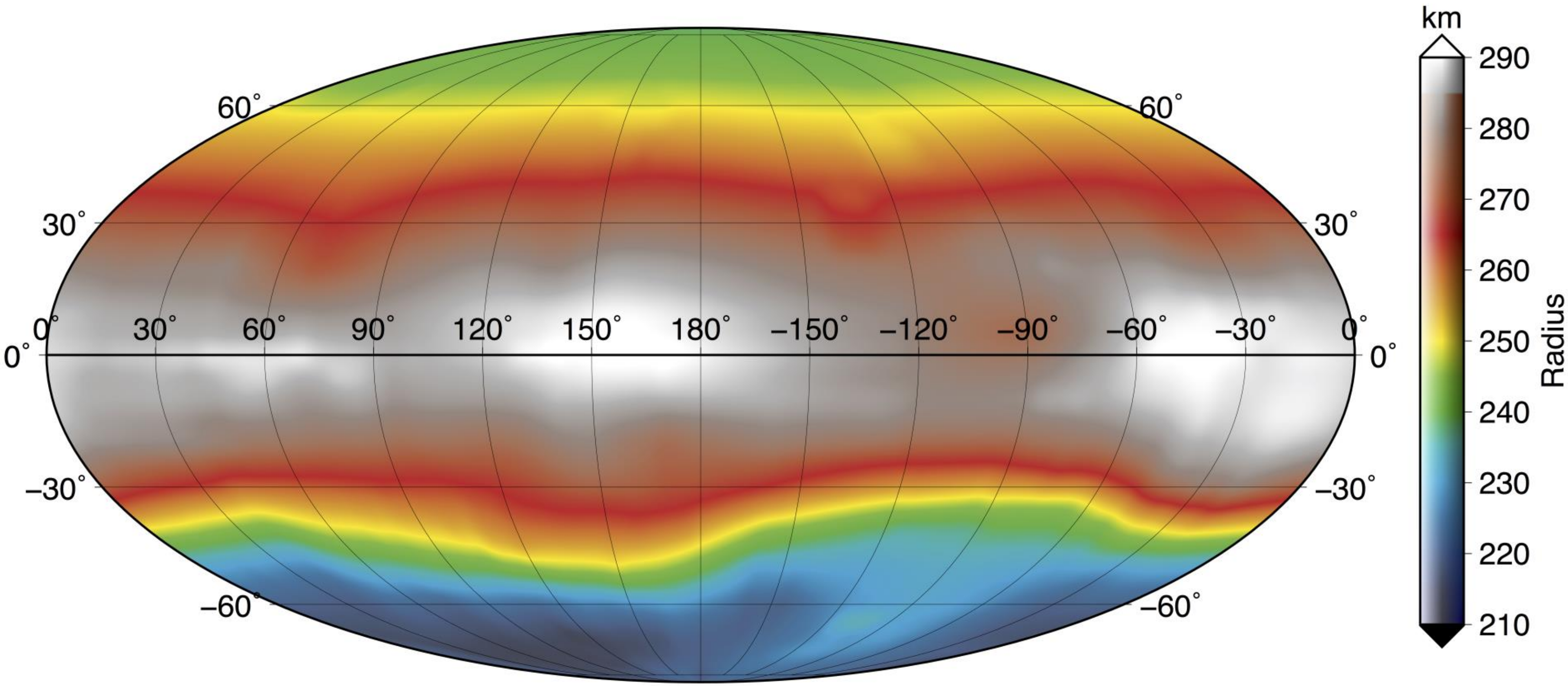
- HED-meteorites enabled detailed geochemical modeling of Vesta
- Ceres interiors were essentially unconstrained



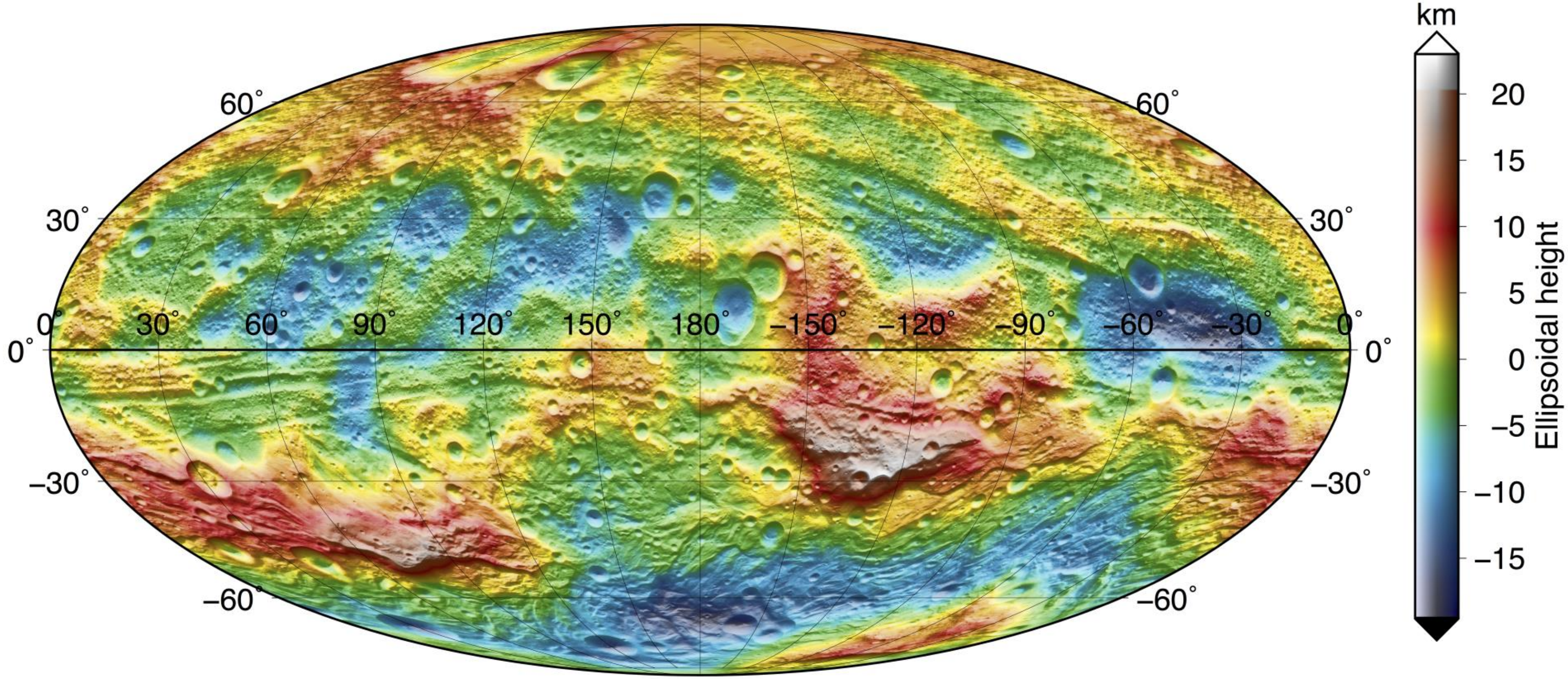
Dawn *geophysical* data

- Shape model
  - Stereophotogrammetry (SPG) from DLR
  - Stereophotoclinometry (SPC) from JPL
  - Mutually consistent with the accuracy much better than the spatial resolution of gravity field
- Gravity field
  - Accurate up to n = 18 (λ=93 km) for Vesta (Konopliv et al., 2014)
  - Accurate up to n = 17 (λ=174 km) for Ceres (Konopliv et al., 2017)
- Assumptions we have to make:
  - Multilayer model with uniform density layers
  - Range of core densities for Vesta
  - Range of crustal densities from HEDs for Vesta
  - Can't really assume anything for Ceres

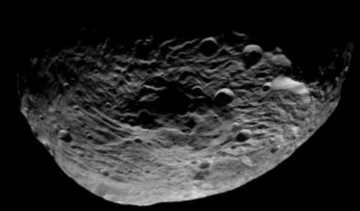
Vesta (Thomas et al, 1997)



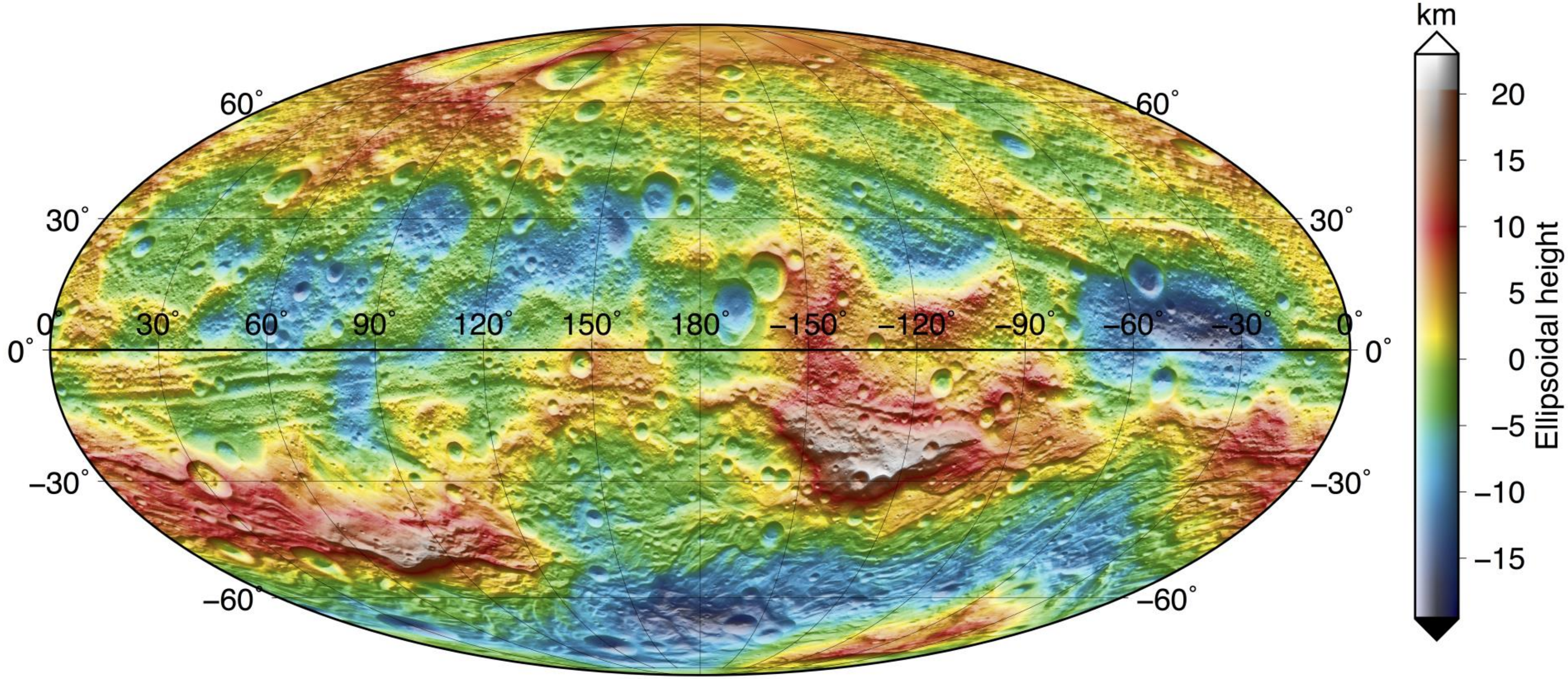
Vesta SPC



Reference ellipsoid:
a = 280.9 km
c = 226.2 km



Vesta SPG



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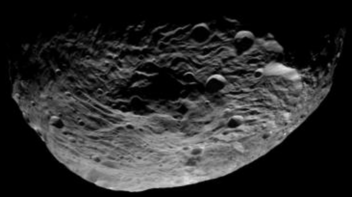
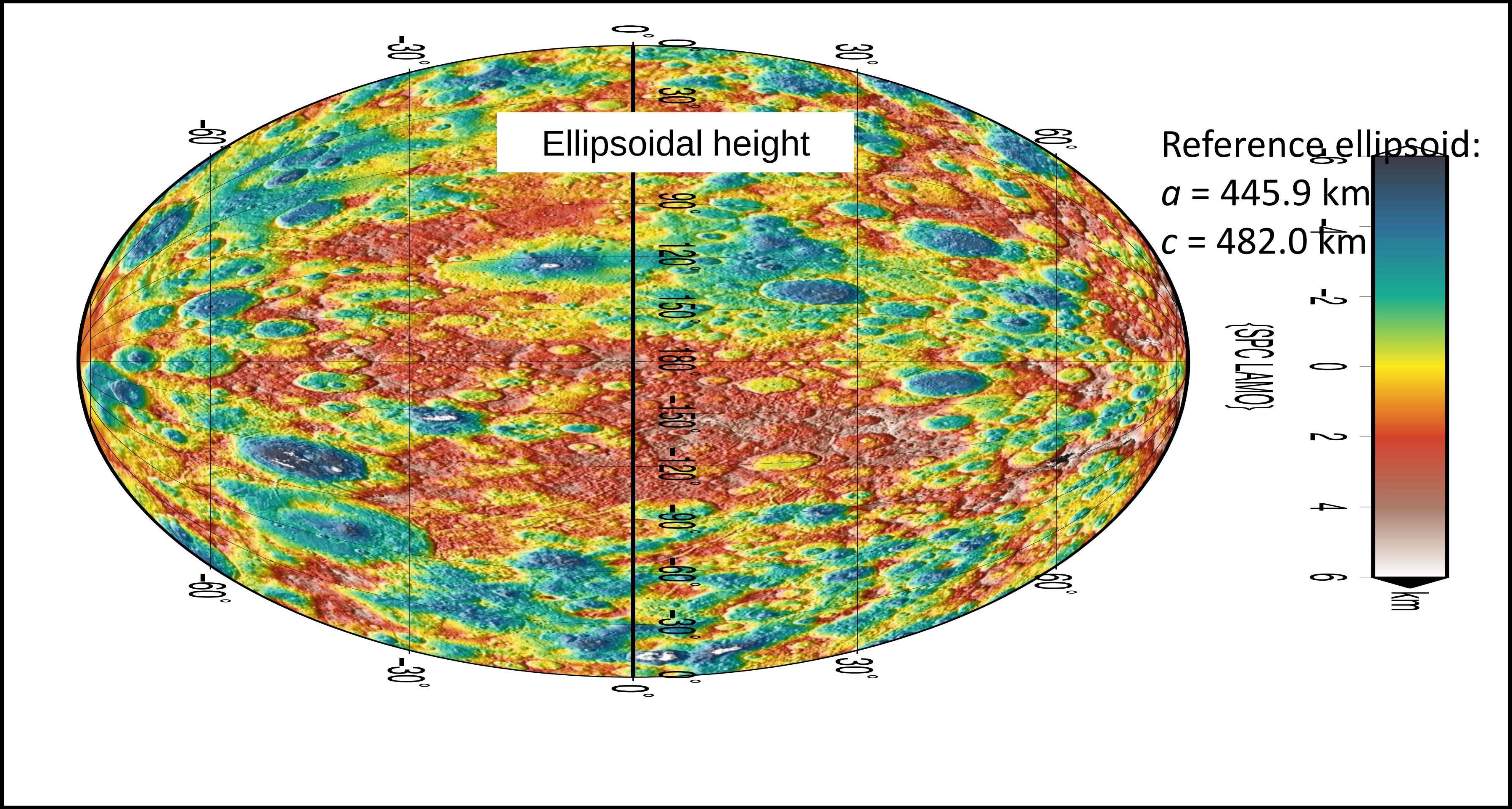
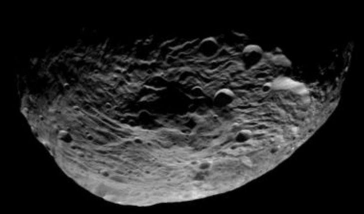
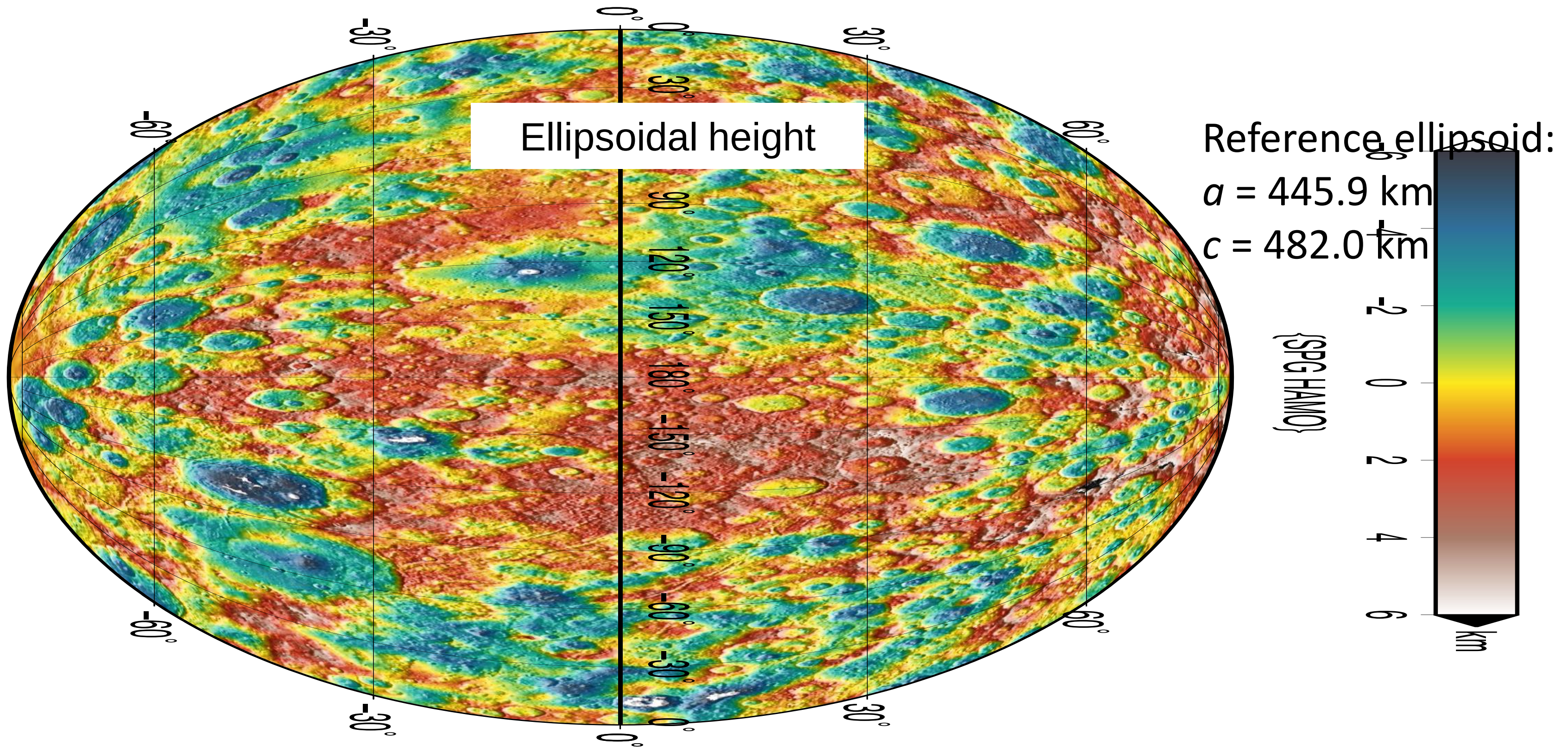


Ceres SPC

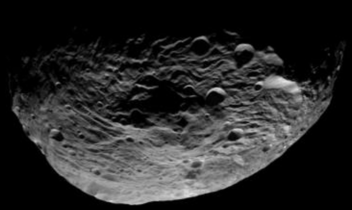

Ellipsoidal height
Reference ellipsoid:
a = 445.9 km
c = 482.0 km
{SPC LAMO}
km
-6
-4
-2
0
2
4
6
0°
30°
60°
90°
120°
150°
180°
-150°
-120°
-90°
-60°
-30°



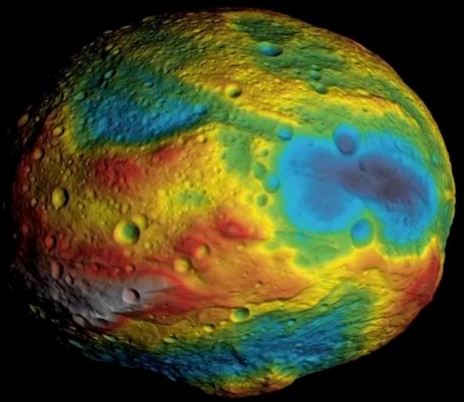
Ceres SPG



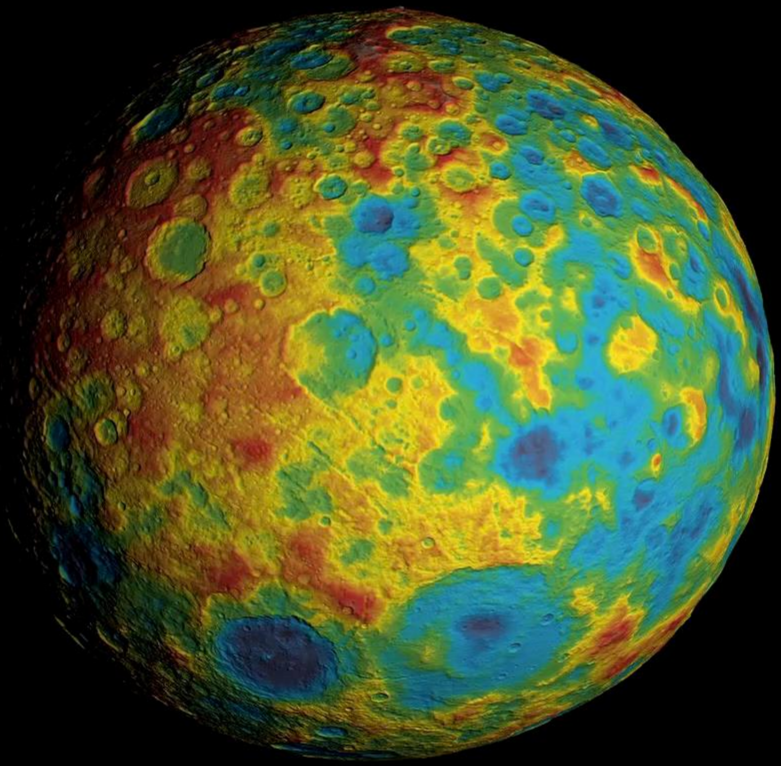
Reference ellipsoid:
a = 445.9 km
c = 482.0 km



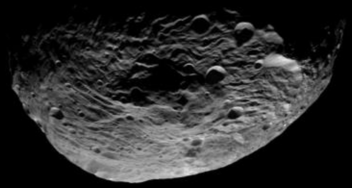
Vesta and Ceres



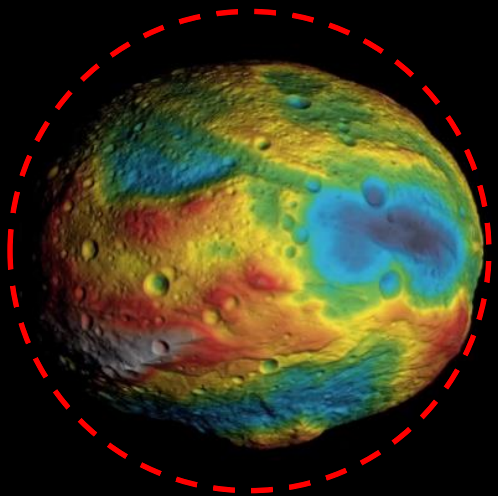
Gaskell, 2012



Park et al., 2016



Vesta and Ceres



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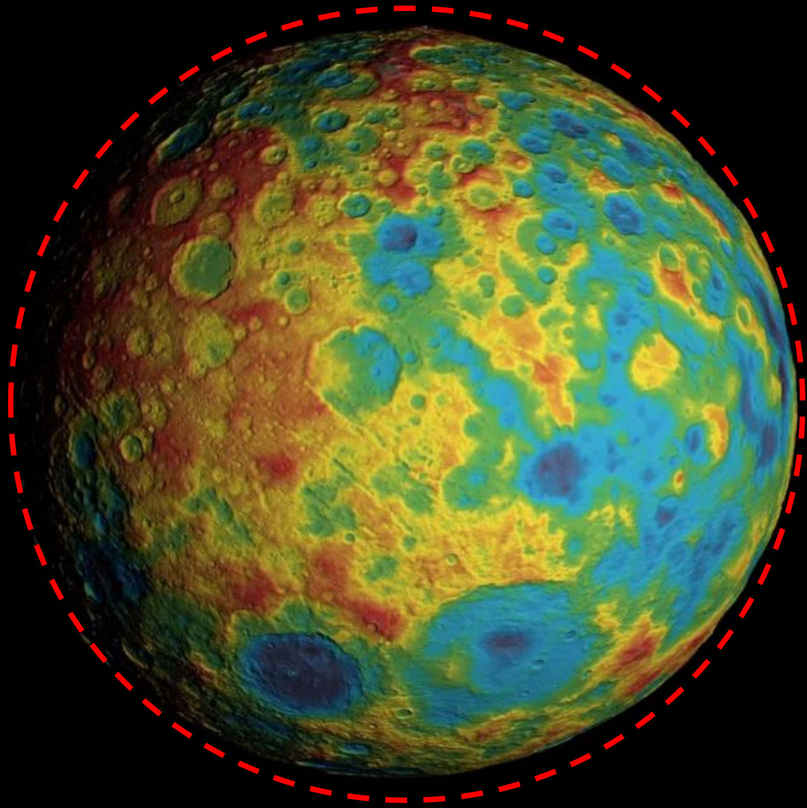


Park et al., 2016

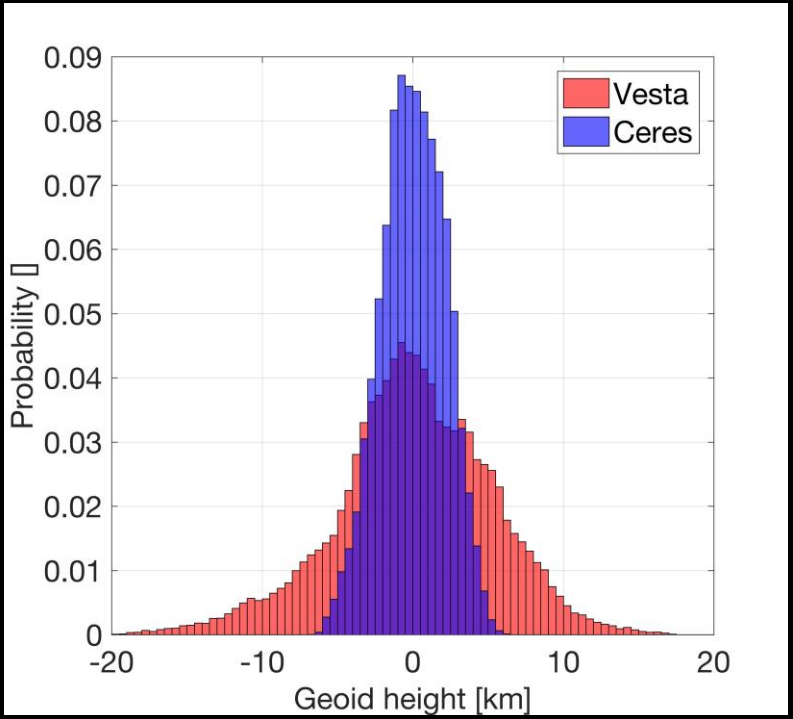
Vesta and Ceres topography

Shape statistics

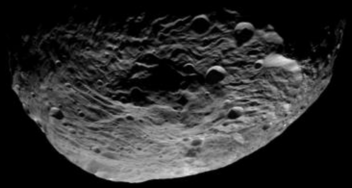
Parameter	Vesta		Ceres
Radius range (km)	80.1	>	44.5
Polar flattening	0.2038	>	0.0770
Equatorial flattening	0.0262	>	0.0043
equatorial/polar	12.9%	>	5.6%
Geoidal height range (km)	37.9	>	13.2
Geoidal height RMS (km)	5.2	>	2.1

- Ceres is closer to hydrostatic equilibrium than Vesta
- Smoother topography at Ceres

Hypsograms of Vesta and Ceres

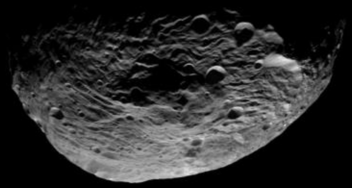


**Hypsogram* is a fancy word for the "histogram of elevations"

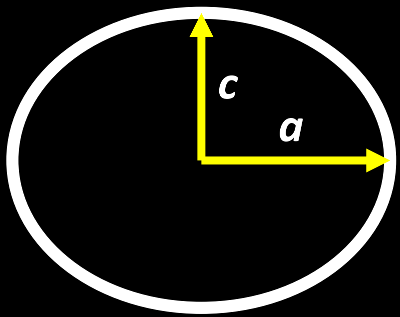


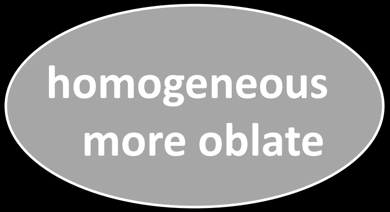
How we use shape data?

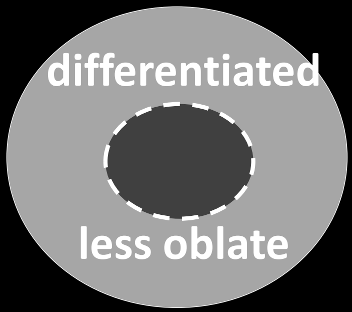
- **Hydrostatic equilibrium**
- **Isostatic compensation**
- **Viscous relaxation**

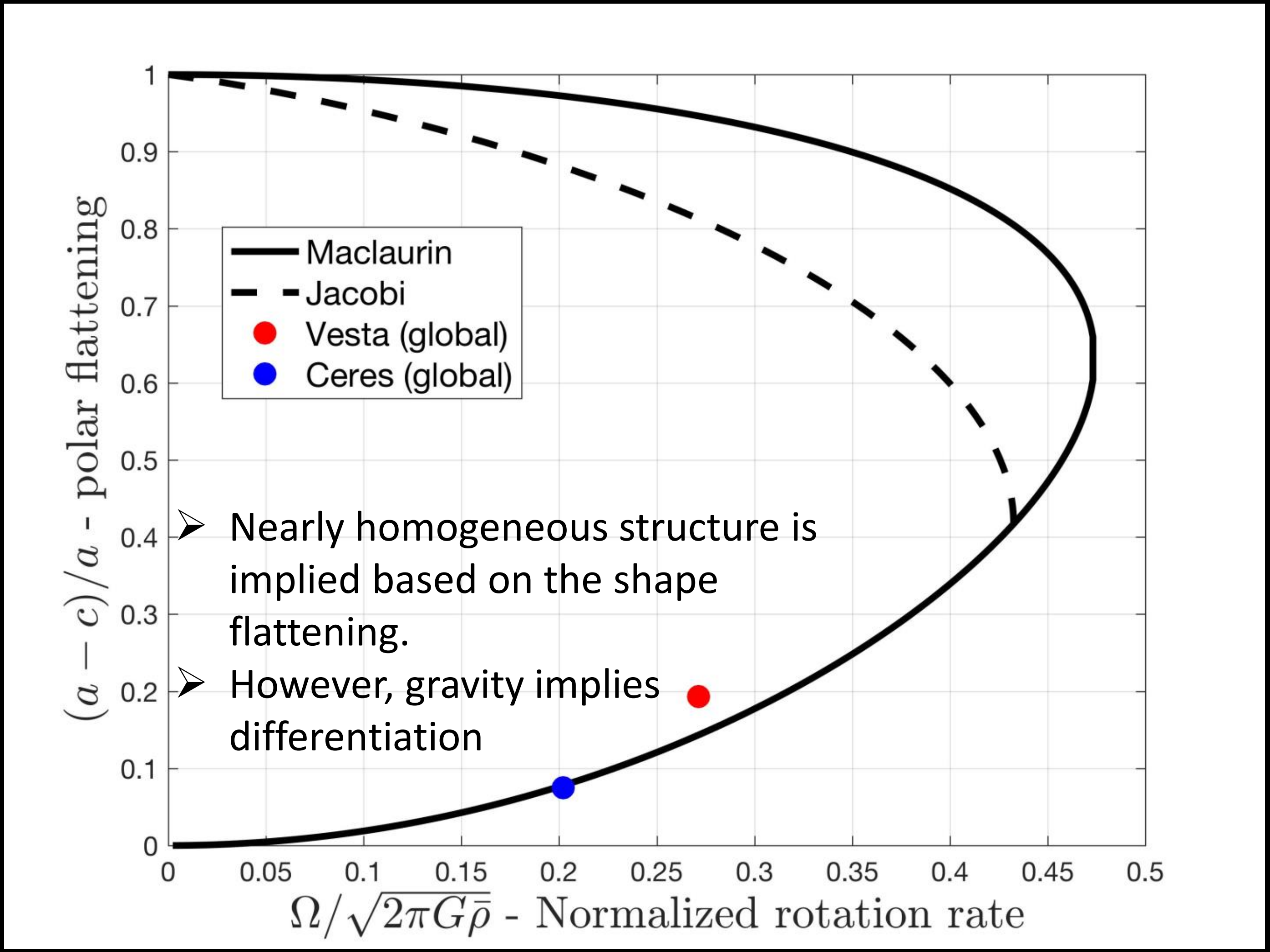


Hydrostatic equilibrium

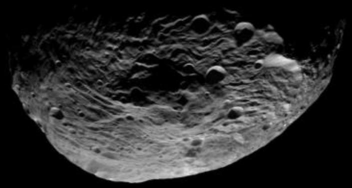








- Nearly homogeneous structure is implied based on the shape flattening.
- However, gravity implies differentiation



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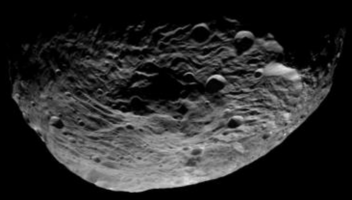
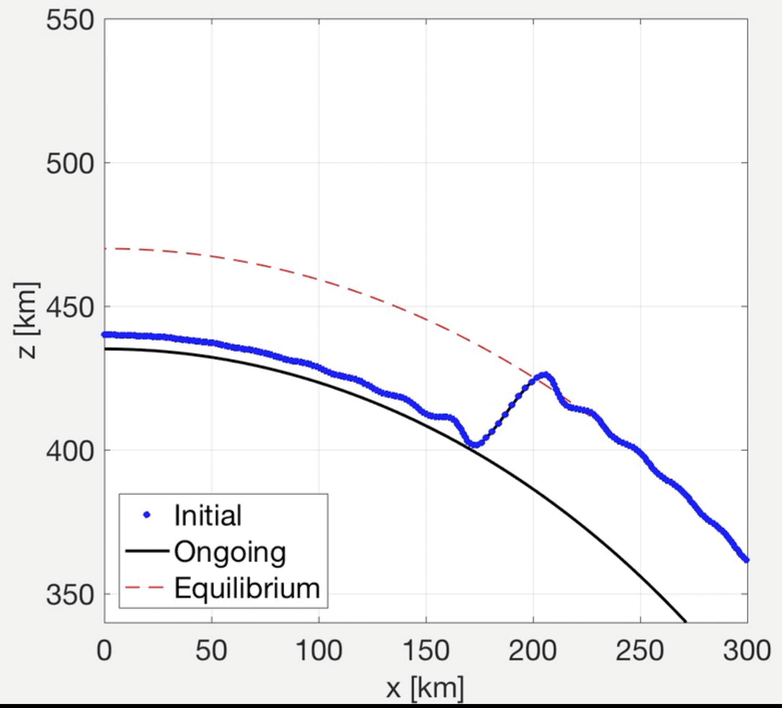


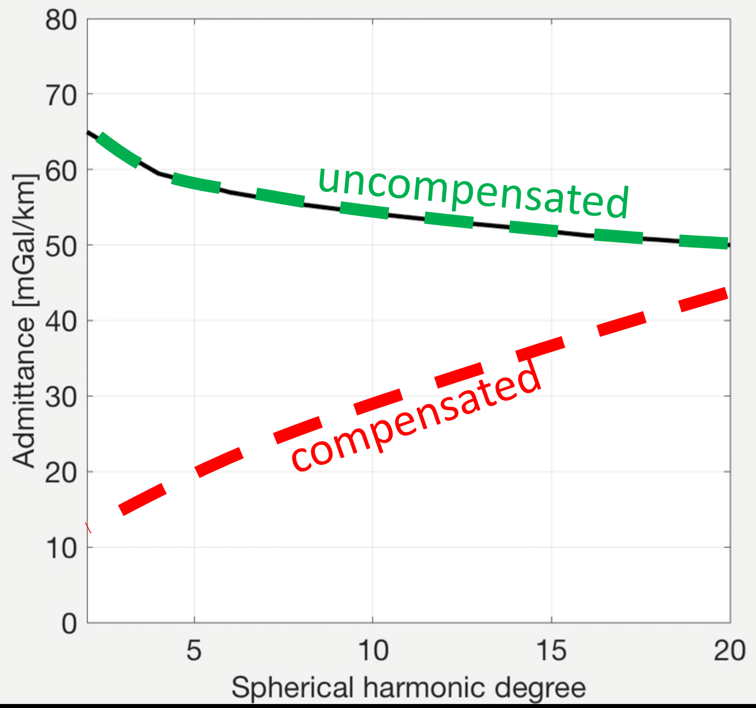
Isostatic compensation

- Example of a spherical cap (depression) relaxation

Interface evolution

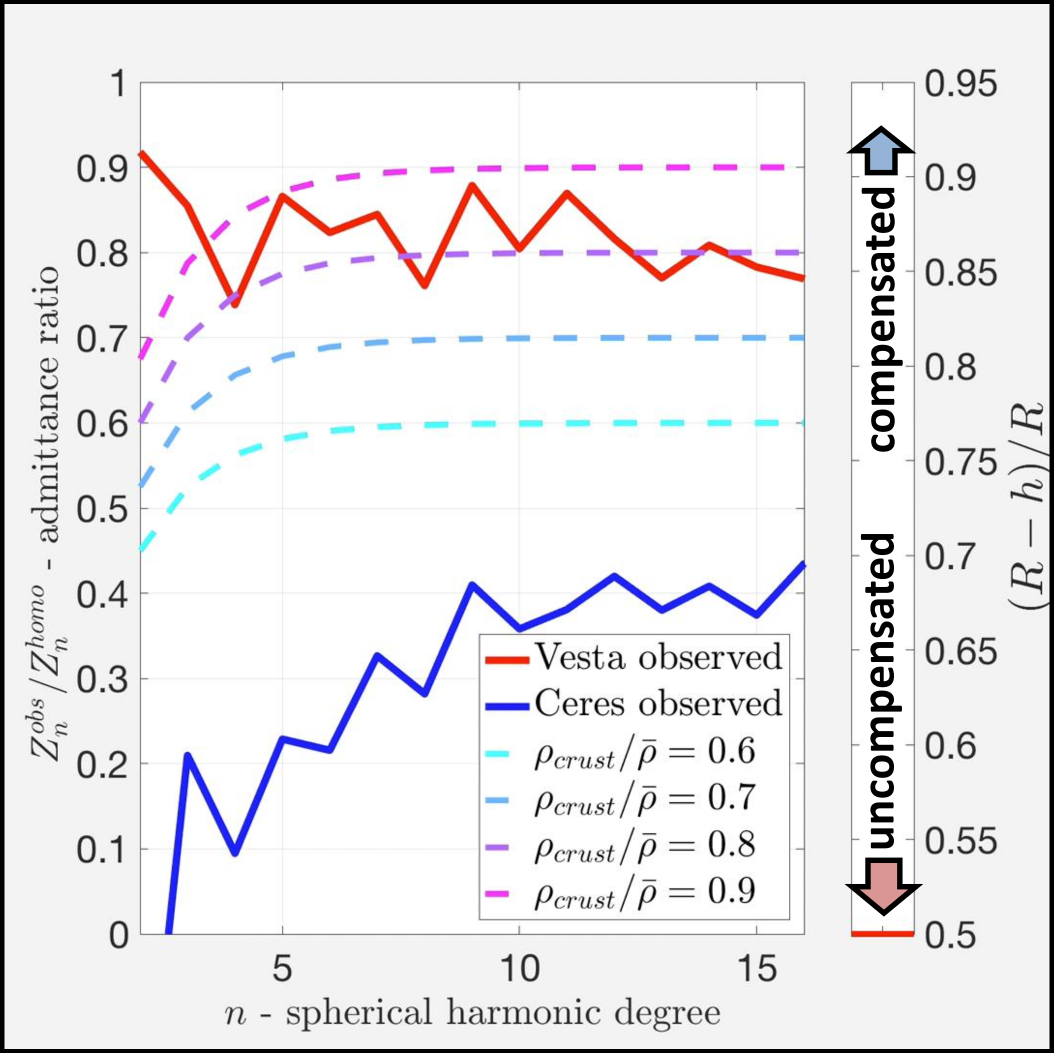
Admittance evolution = ratio of gravity to topography

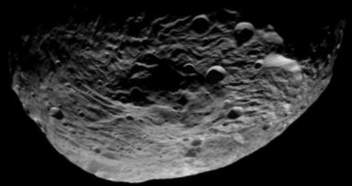




Isostatic compensation

- **Admittance (*Z*) is a ratio of gravity to topography.**
- **Isostatically compensated and uncompensated topography have different admittances.**
- **Modeling of isostasy allows constraining the density and thickness of the compensated layer as well as the density contrast.**

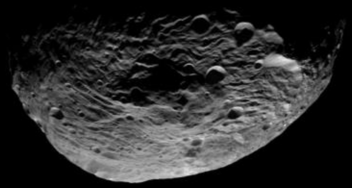




Compensation for Vesta and Ceres

- Vesta topography is <u>uncompensated</u>
- Vesta acquired most of its topography when the crust was already <u>cool and not-relaxing</u>

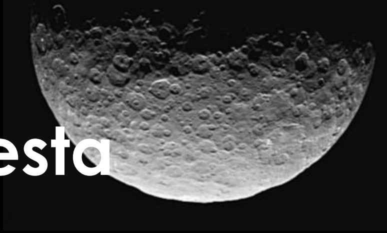
- Ceres topography is <u>compensated</u>
- Lower viscosities (compared to Vesta) enabled <u>relaxation</u> of topography to the isostatic state



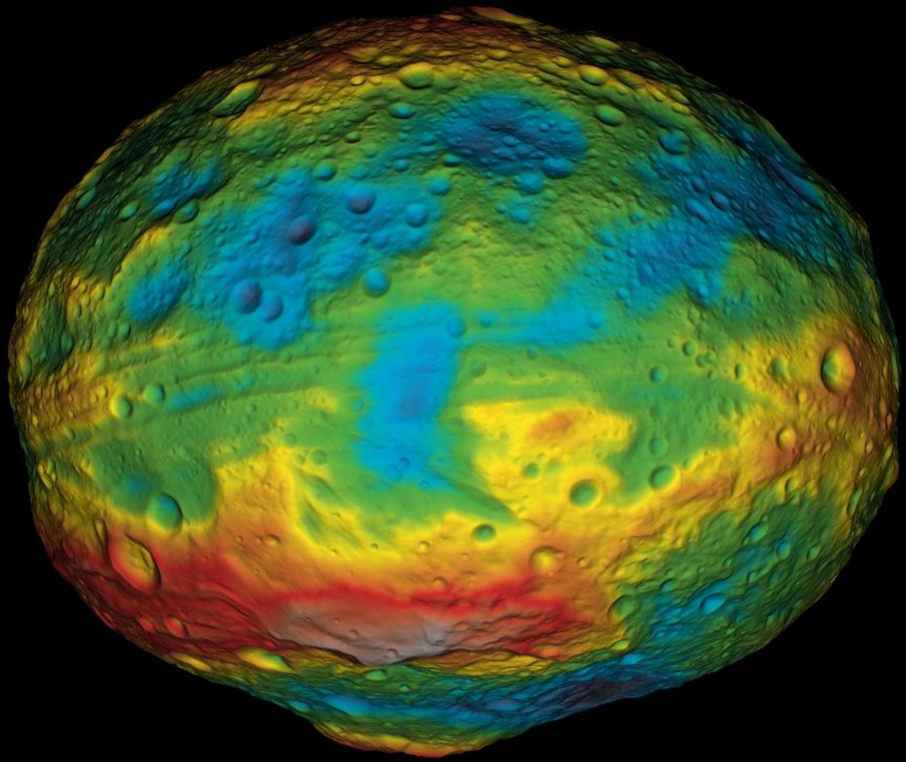
How do we use shape data?

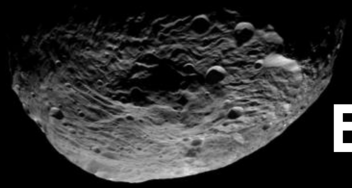
- Hydrostatic equilibrium
- Isostatic compensation
- Viscous relaxation

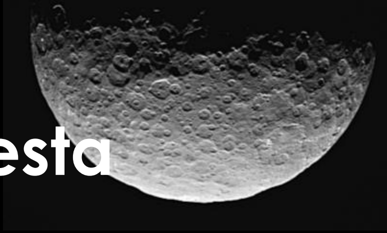
Early efficient viscous relaxation of Vesta



- **Vesta was likely close to hydrostatic equilibrium in its early history (Fu et al., 2014).**
- **Vesta's northern terrains likely reflect its pre-impact equilibrium shape.**
- **Major impact occurred when Vesta was effectively non-relaxing leading to uncompensated Rheasilvia and Veneneia basins.**







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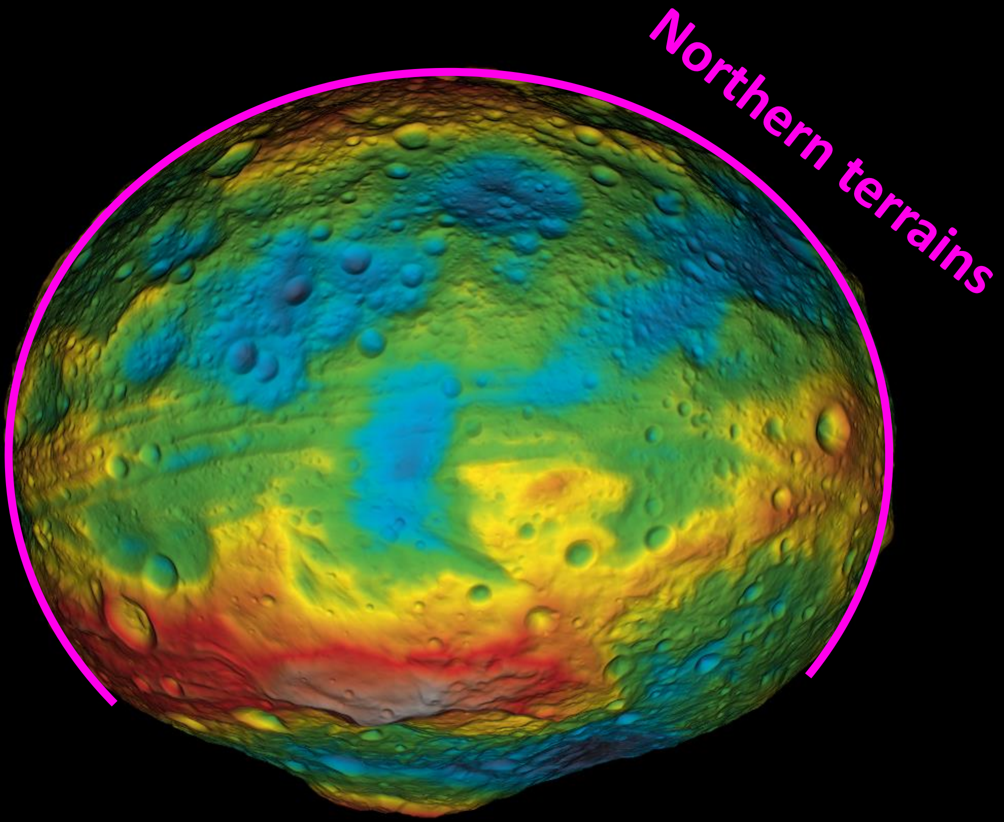

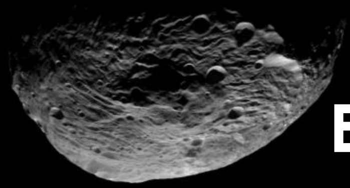

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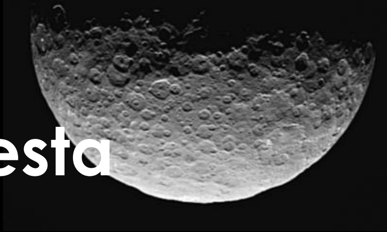

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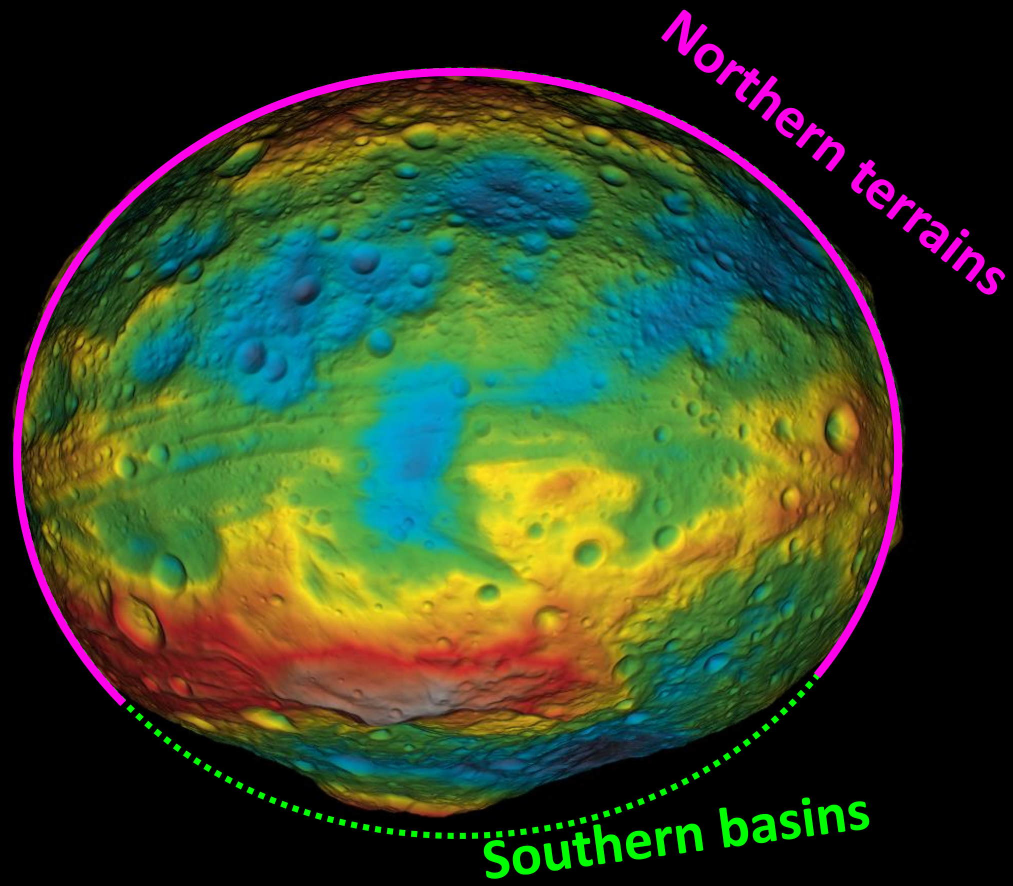

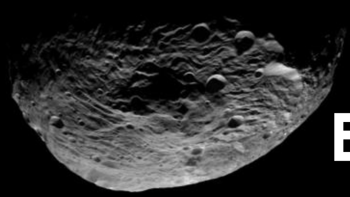

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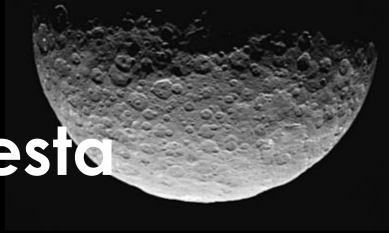
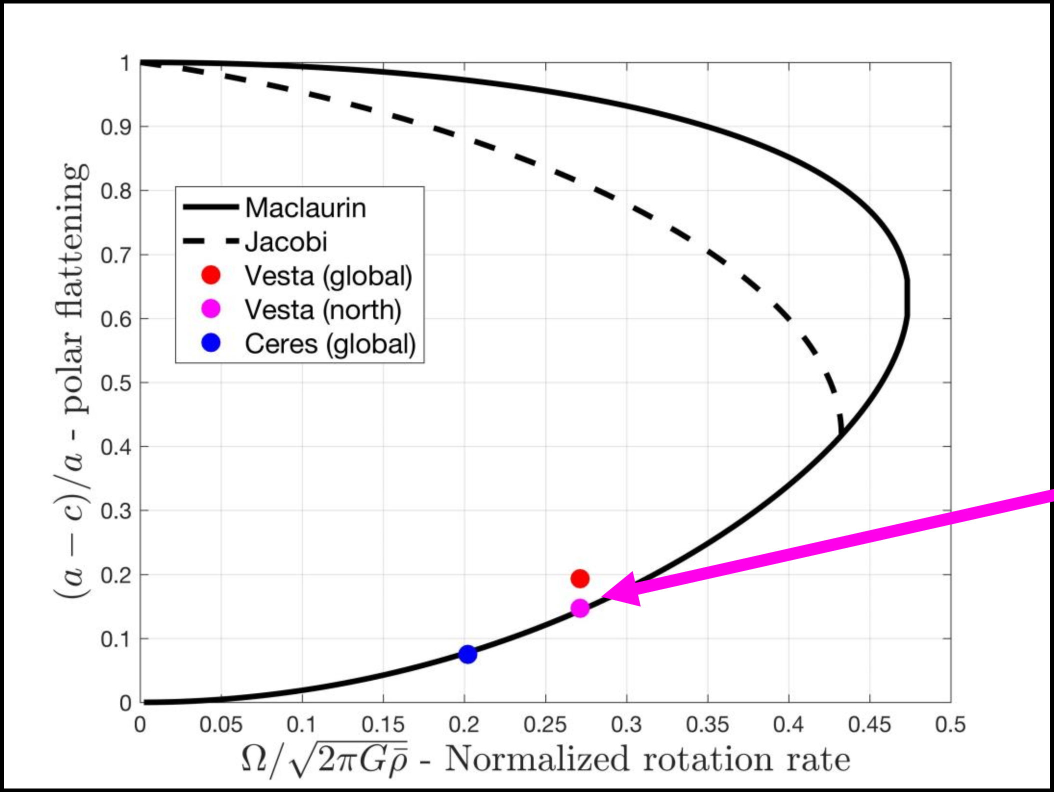
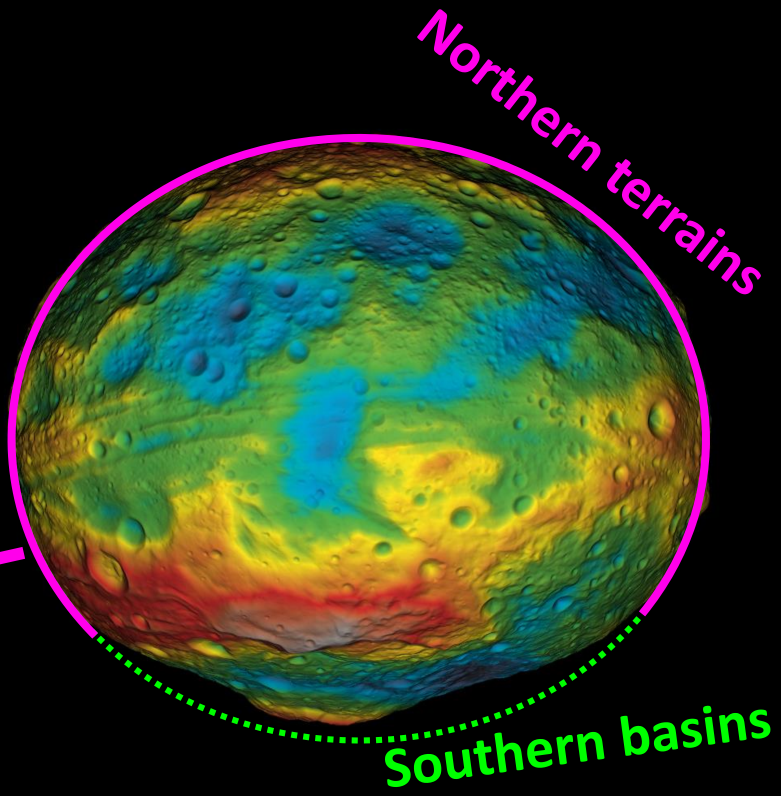
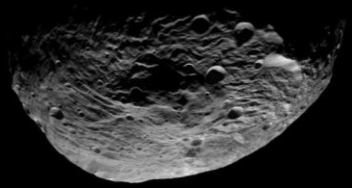






Viscous relaxation on Ceres

- Bland et al., 2013 predicted that craters on Ceres would quickly relax in an ice-dominated shell
  - Equatorial warmer craters would relax faster than colder polar craters
- Bland et al., 2016 did not find that evidence for such relaxation pattern
  - No latitude dependence of crater depth



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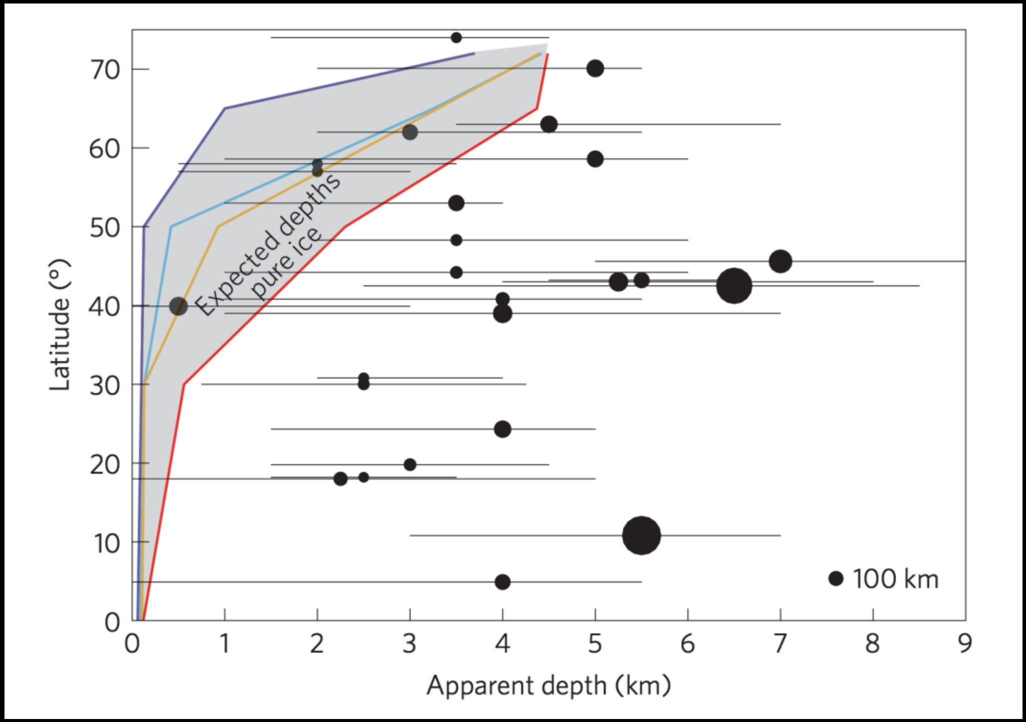
Crater depth study

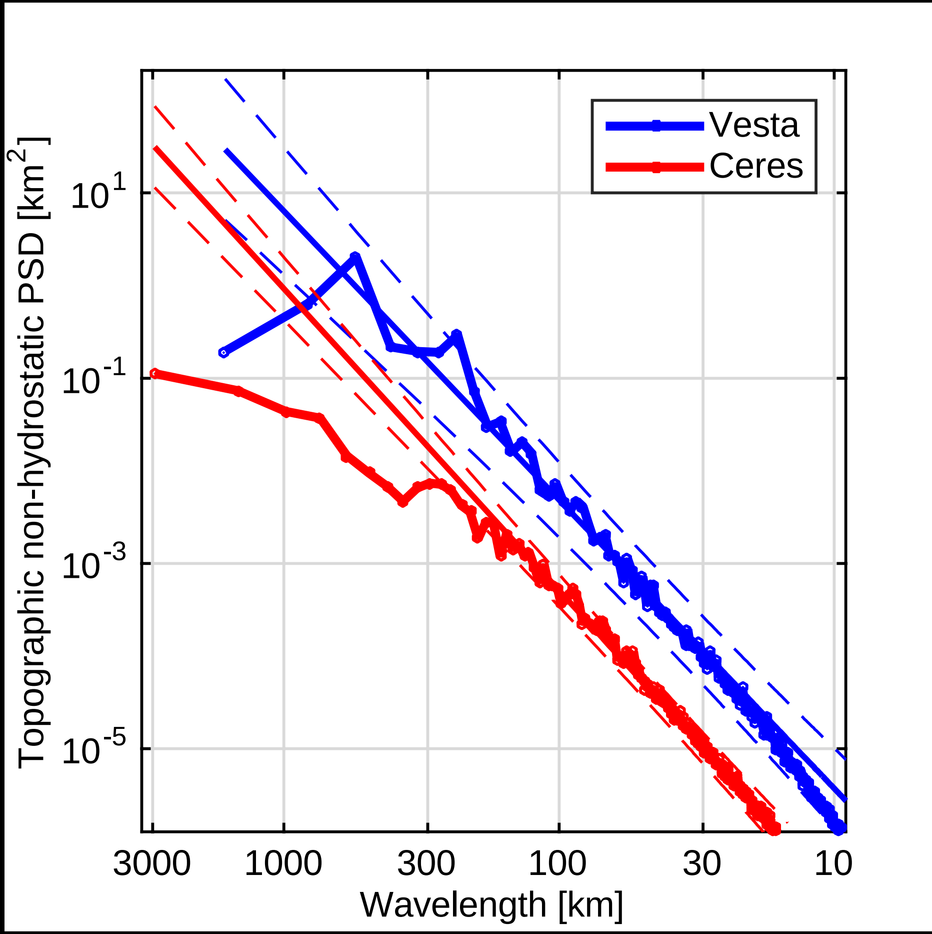


Evidence for viscous relaxation

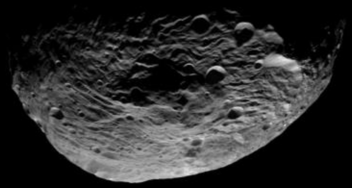
- **More general approach: <u>study topography power spectrum</u>**

- **Power spectra for Vesta closely fits with the power law to the lowest degrees (λ < 750 km)**

- **Ceres power spectrum deviates from the power law at λ > 270 km**



Ermakov et al., 2017



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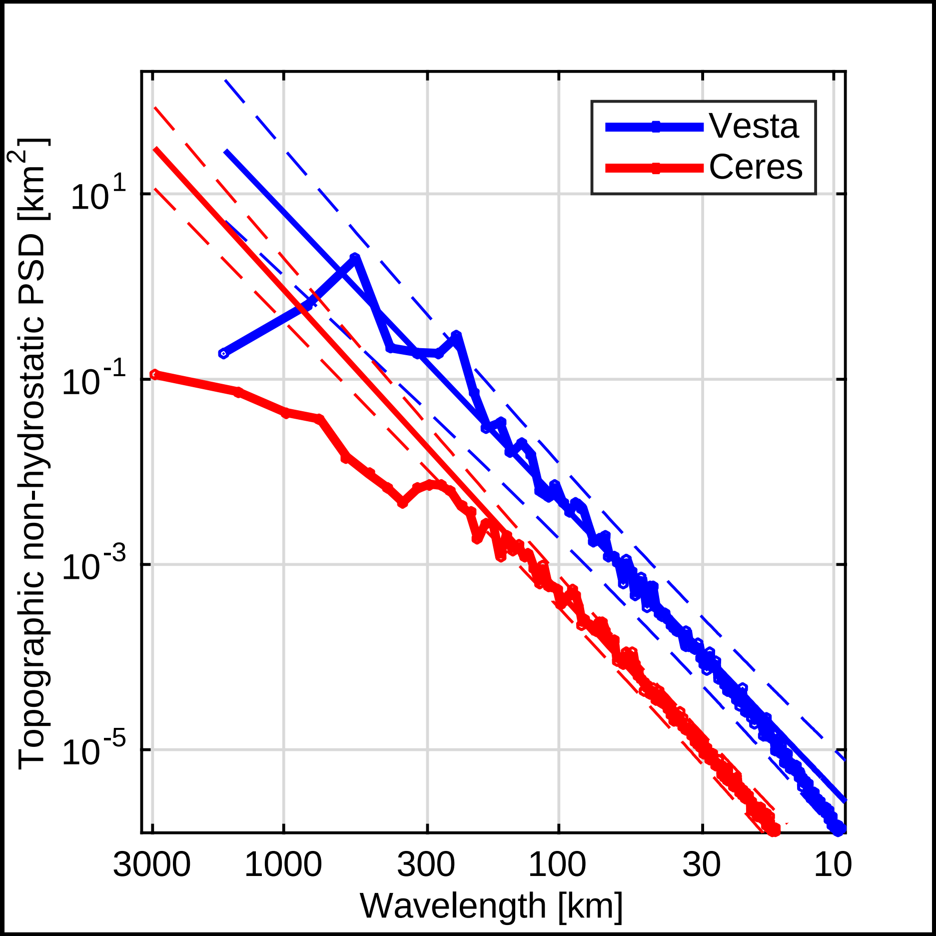

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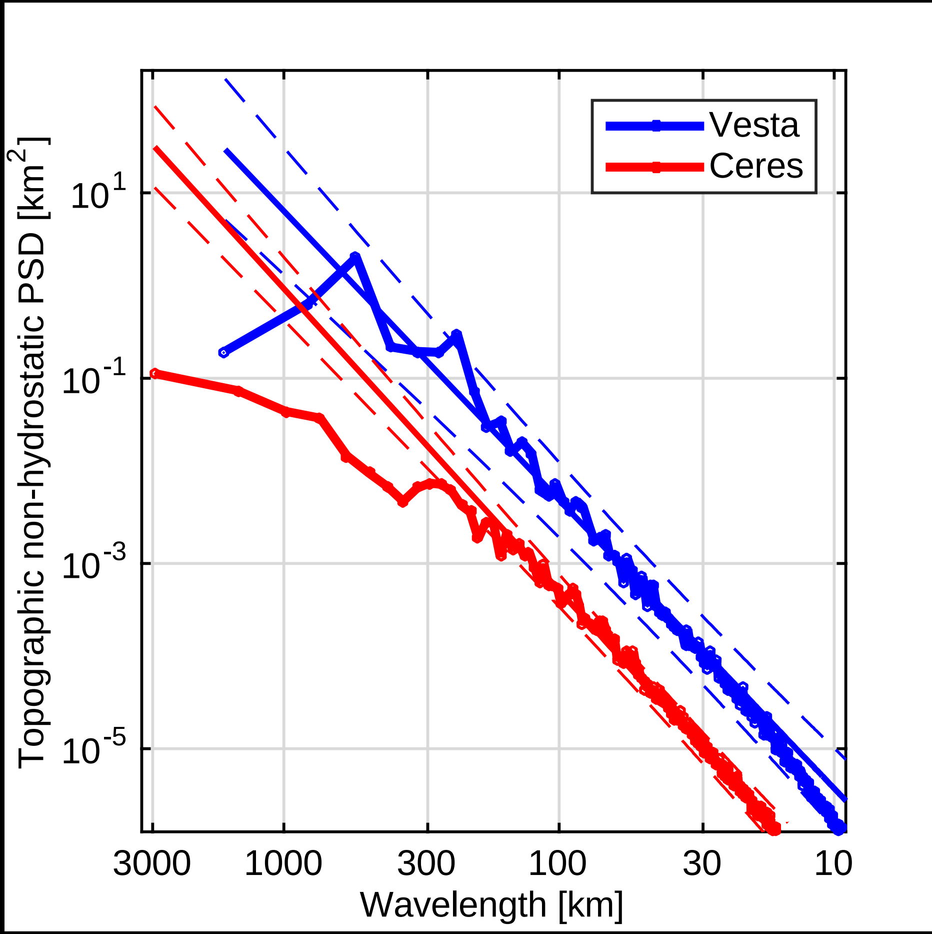

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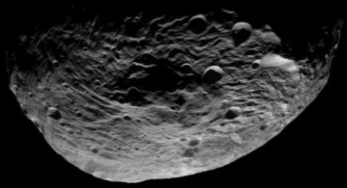
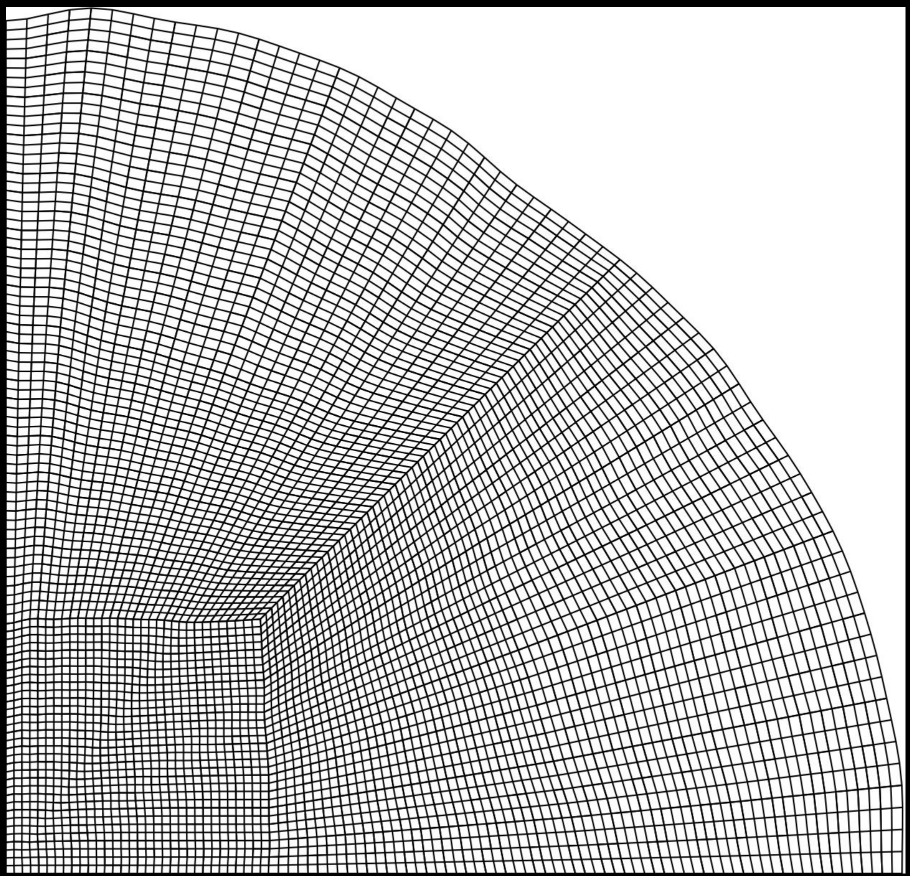
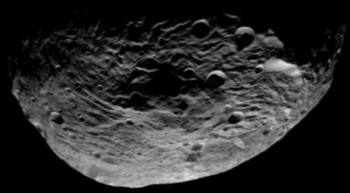


Finite element model



Fu et al., 2014; Fu et al, 2017

- **Assume a density and rheology structure**
- **Solve Stokes equation for an incompressible flow using deal.ii library**
- **Compute the evolution of the outer surface power spectrum**



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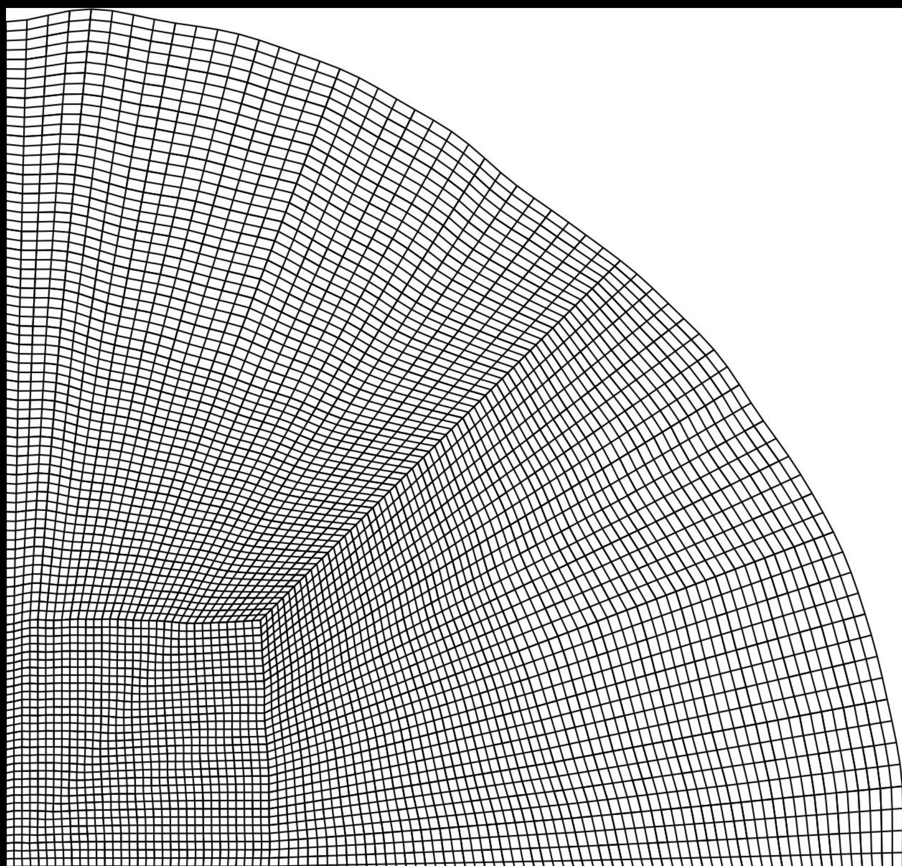

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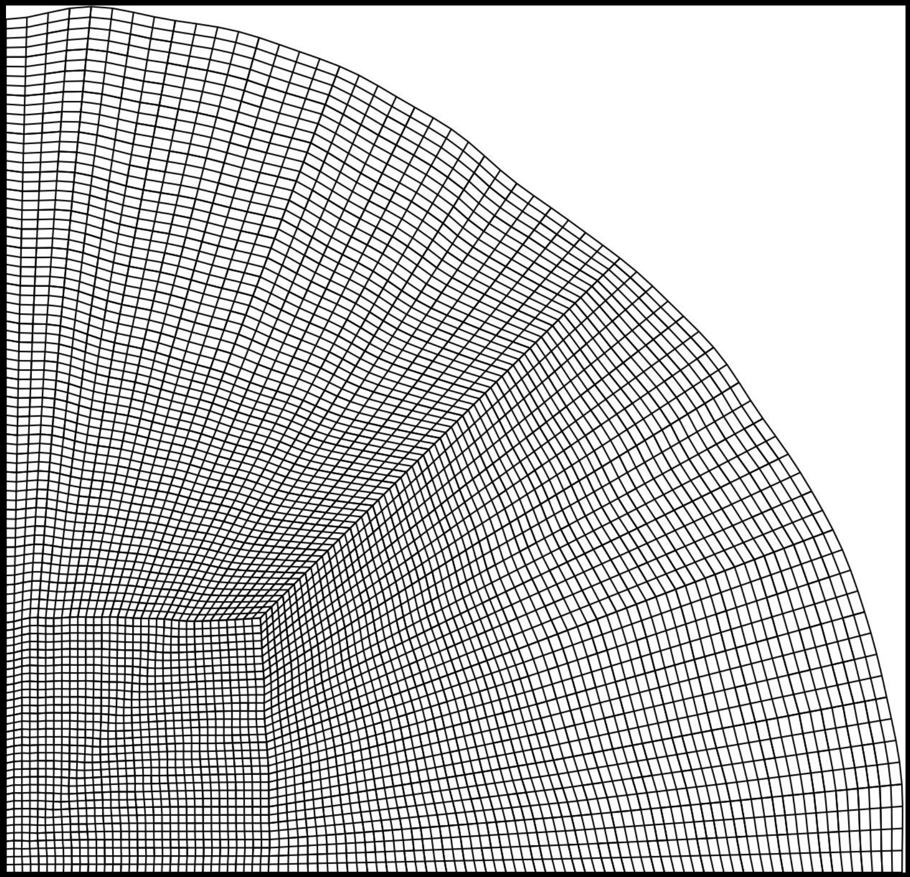

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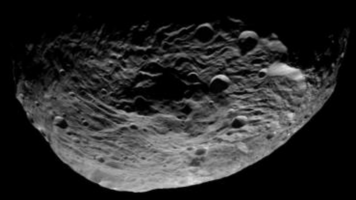
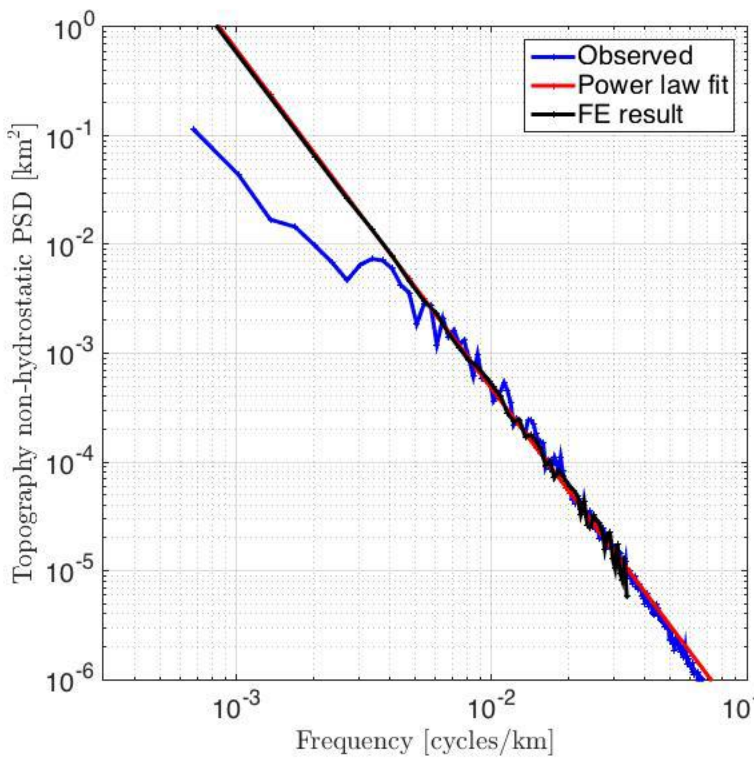
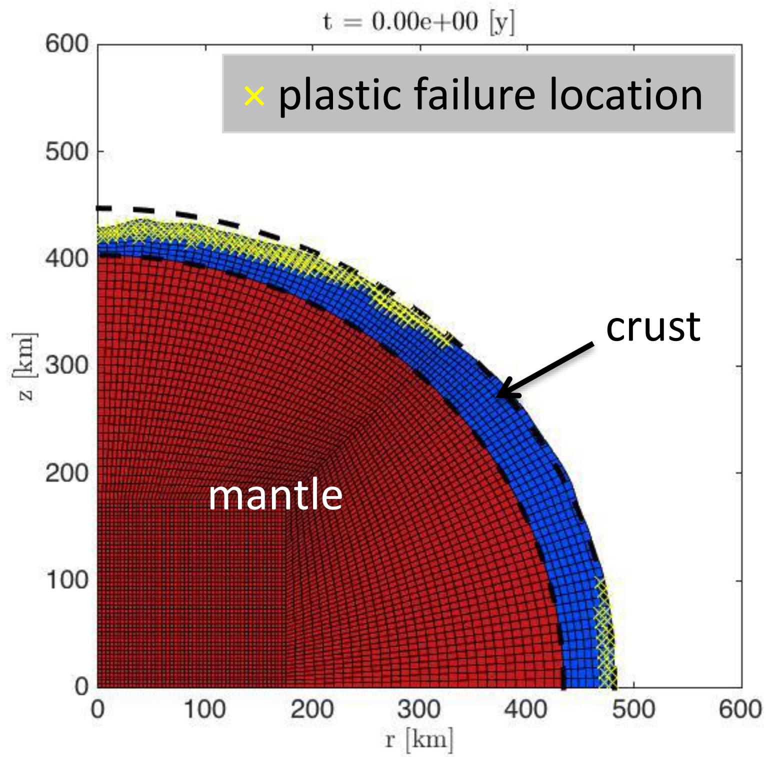


Example of a FE modeling run

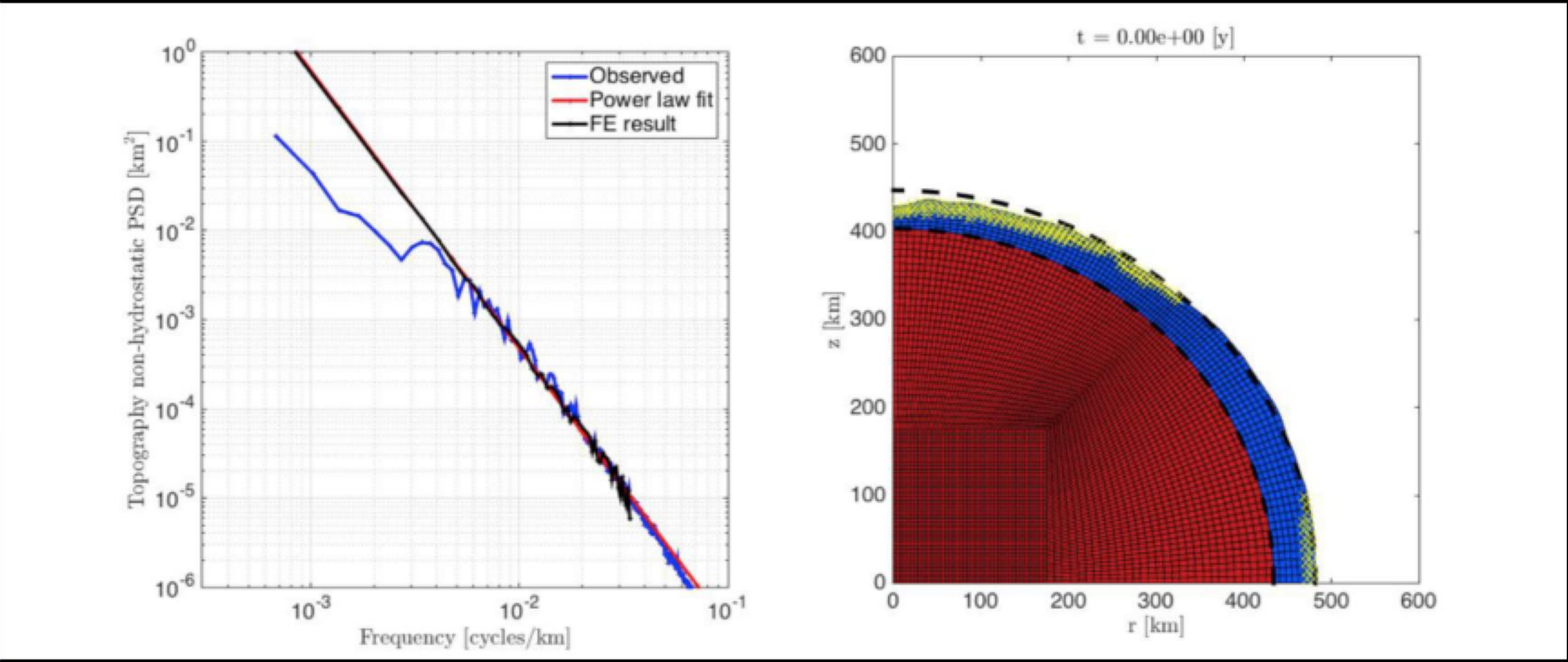
relaxation in the frequency domain

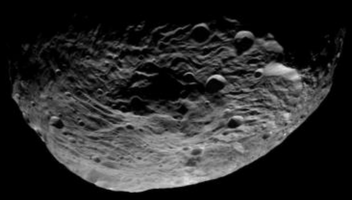


relaxation in the spatial domain



Finite element modeling results





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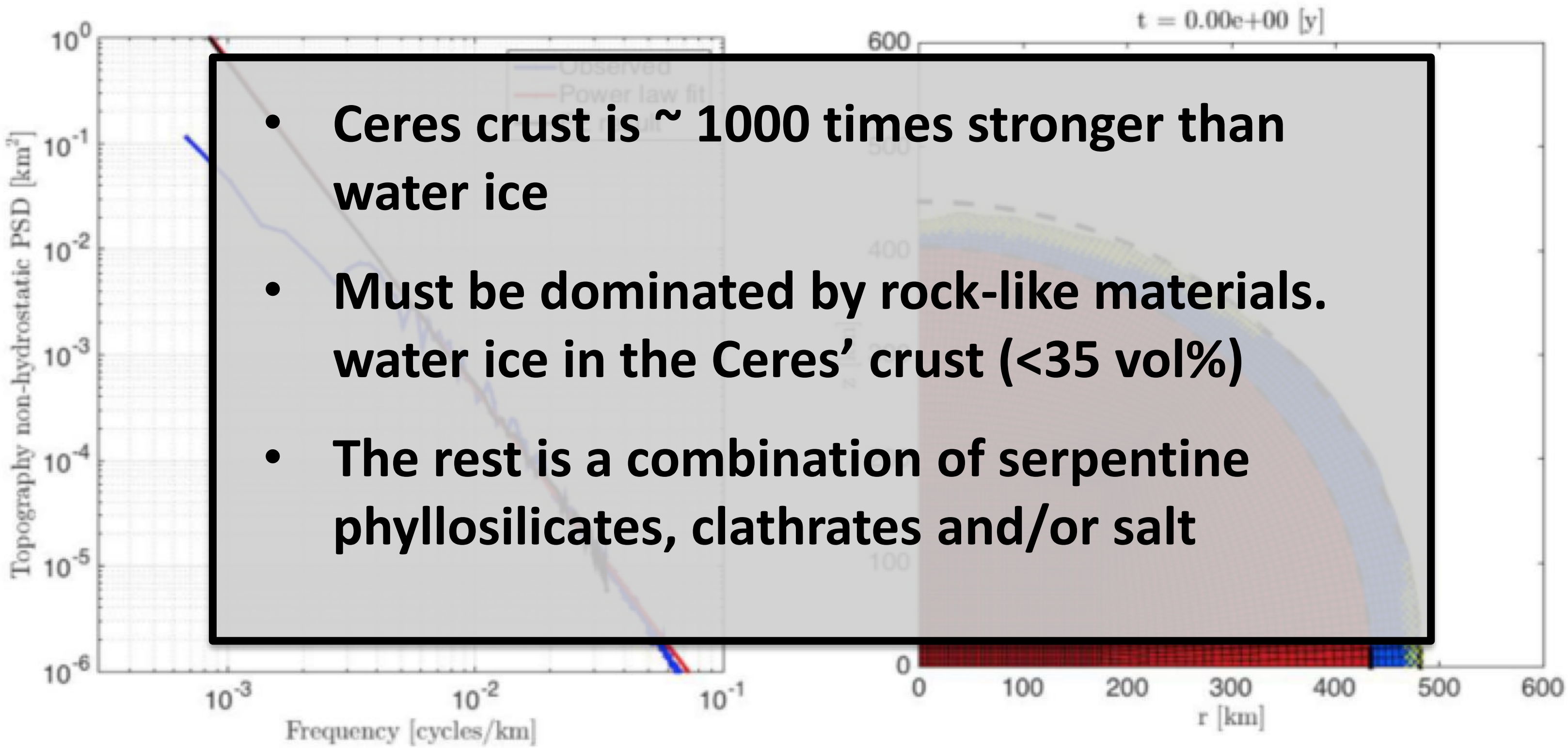
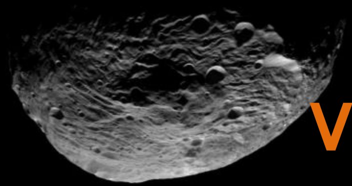
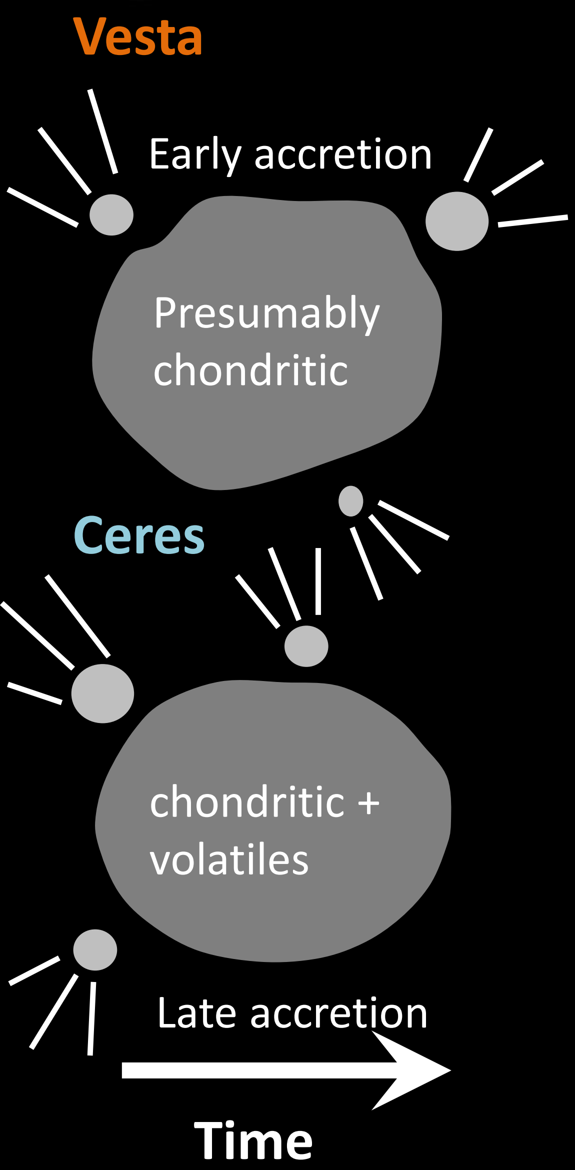


- **Ceres crust is ~ 1000 times stronger than water ice**
- **Must be dominated by rock-like materials. water ice in the Ceres' crust (<35 vol%)**
- **The rest is a combination of serpentine phyllosilicates, clathrates and/or salt**



Vesta and Ceres comparative evolution



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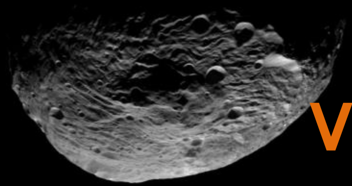

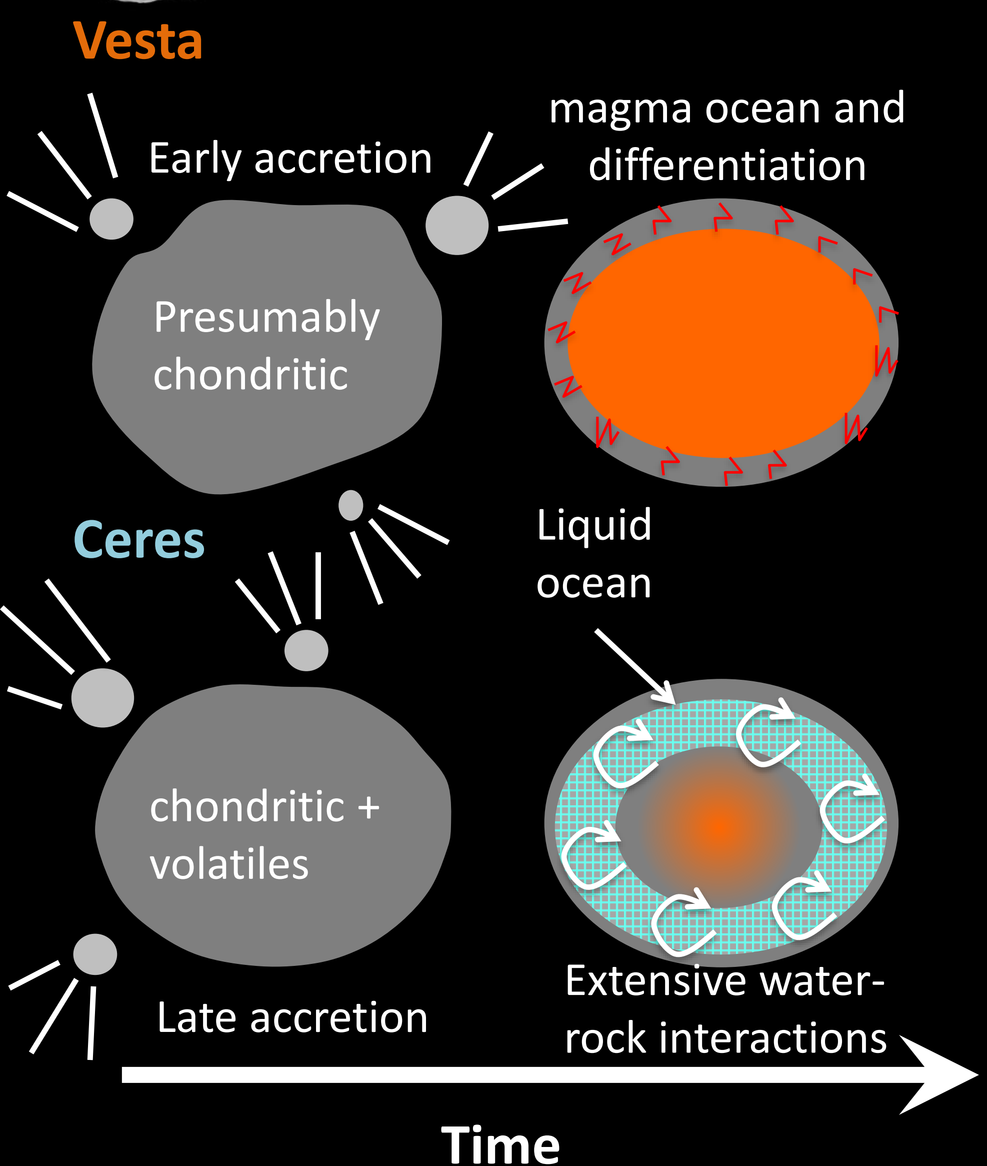

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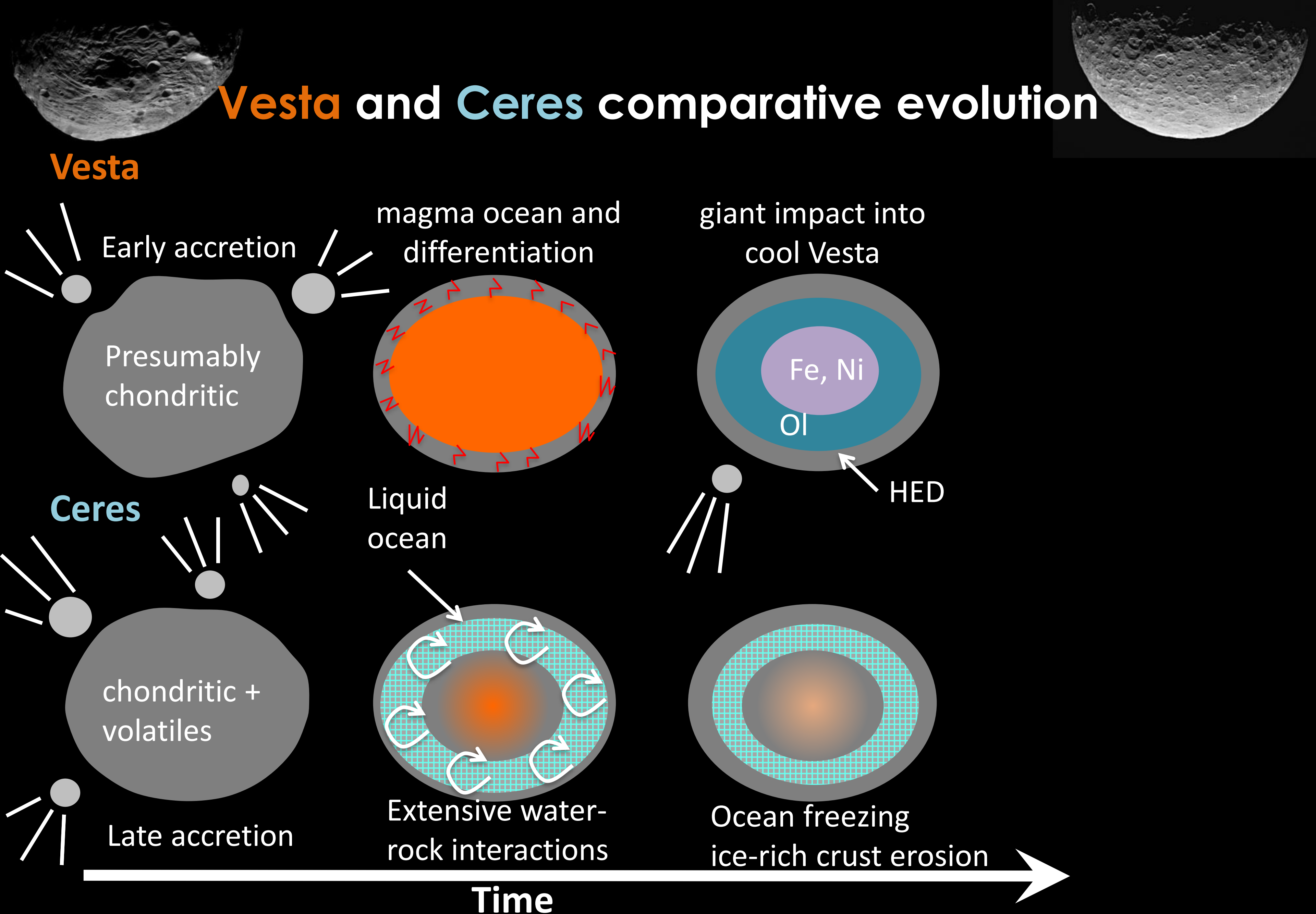

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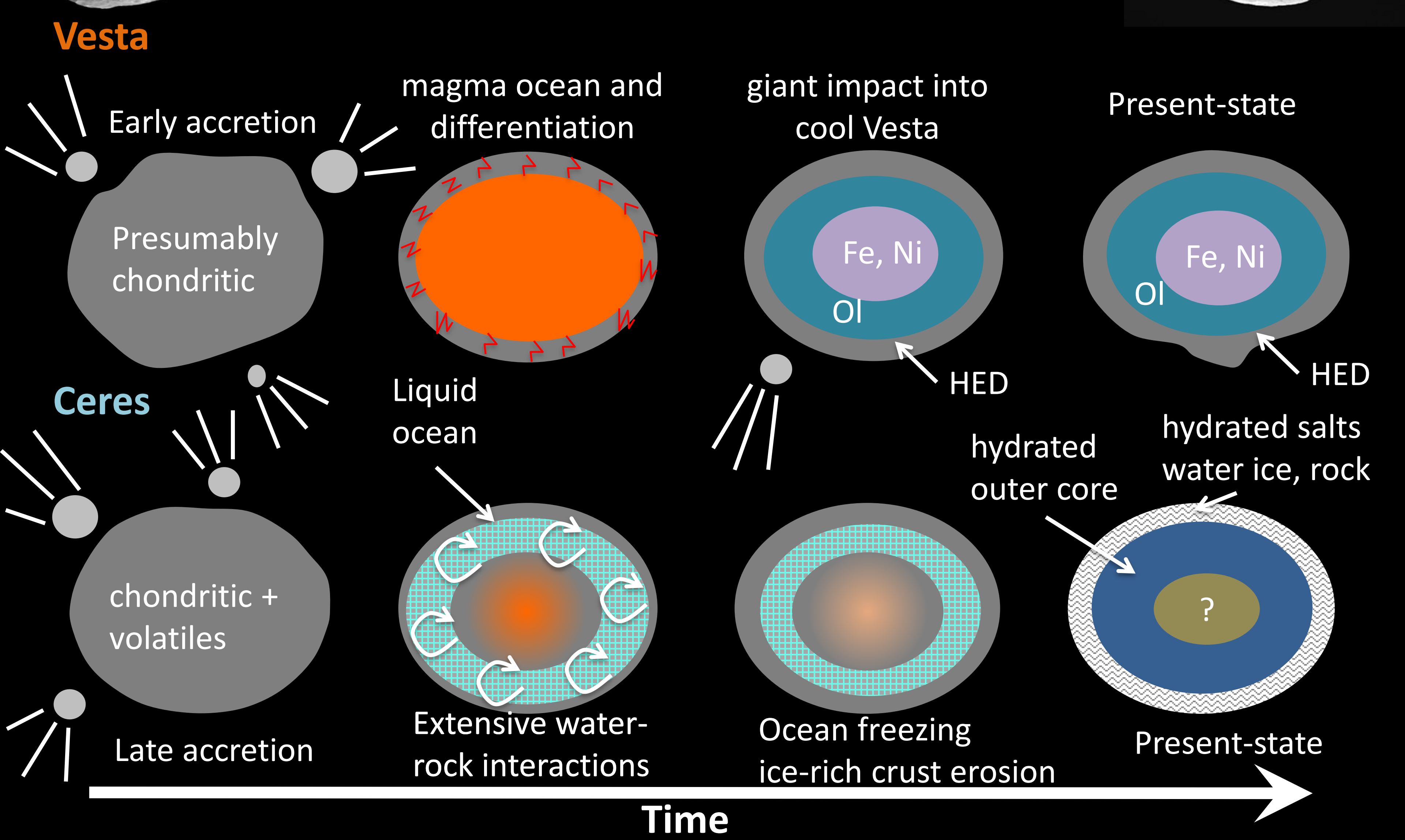
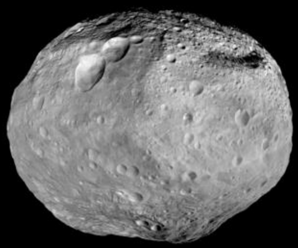
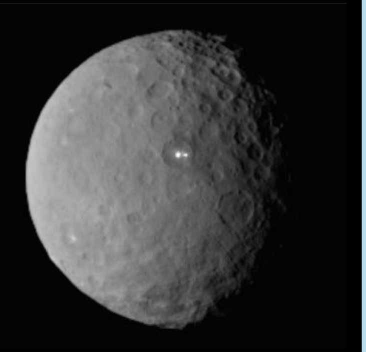


Summary



- Formed early (< 5 My after CAI)
- Once hot and hydrostatic, Vesta is no longer either
- Differentiated interior
- Most of topography acquired when Vesta was already cool => uncompensated topography
- Combination of gravity/topography data with meteoritic geochemistry data provides constraints on the internal structure

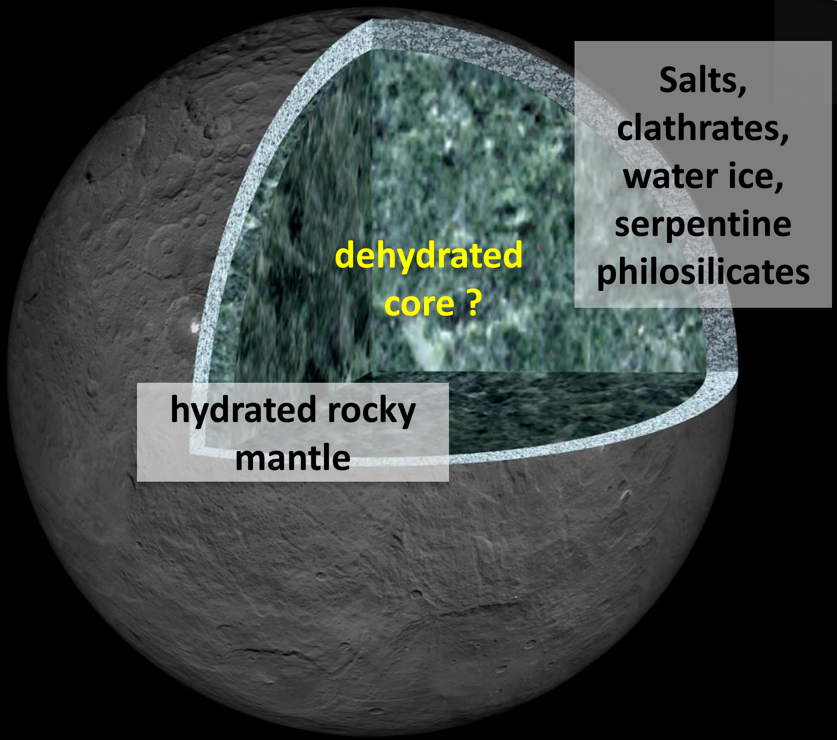


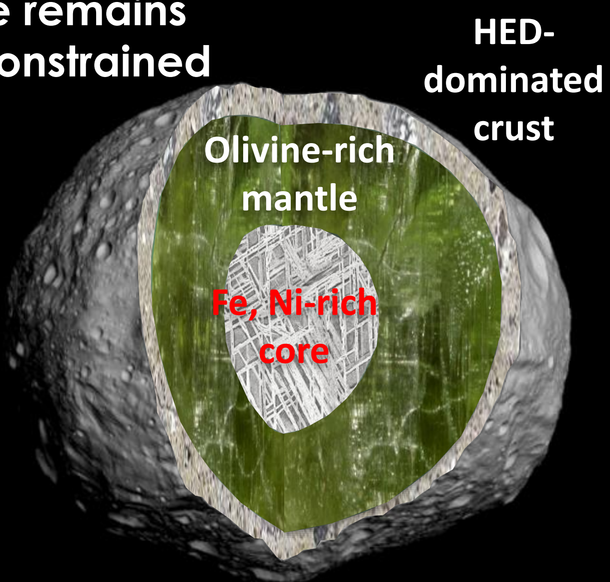
- Cooler history
  - late formation
  - and/or heat transfer due to hydrothermal circulation
- Partially differentiated interior
- Experienced viscous relaxation
- Much lower surface viscosities (compared to Vesta) allowed compensated topography
- Ceres' crust is light (based on admittance analysis) and strong (based on FE relaxation modeling)
- Not much water ice in Ceres crust (<35 vol%) now

Internal structures of Vesta and Ceres

Ceres→

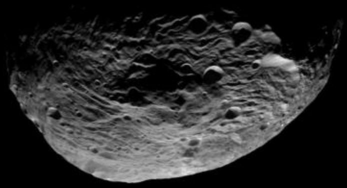
- Crust is light (1.1-1.4 g/cc) and mechanically rock-like w
- Mantle density ~2.4 g/cc and unlithified at least to a depth of 100 km
- Possible dehydrated rocky core remains unconstrained



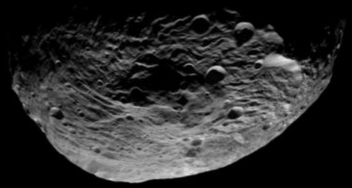


←Vesta

- Crustal density constrained by HEDs and admittance (2.8 g/cc)
- Assuming density of iron meteorites (5-8 g/cc), the core radius is 110 – 155 km

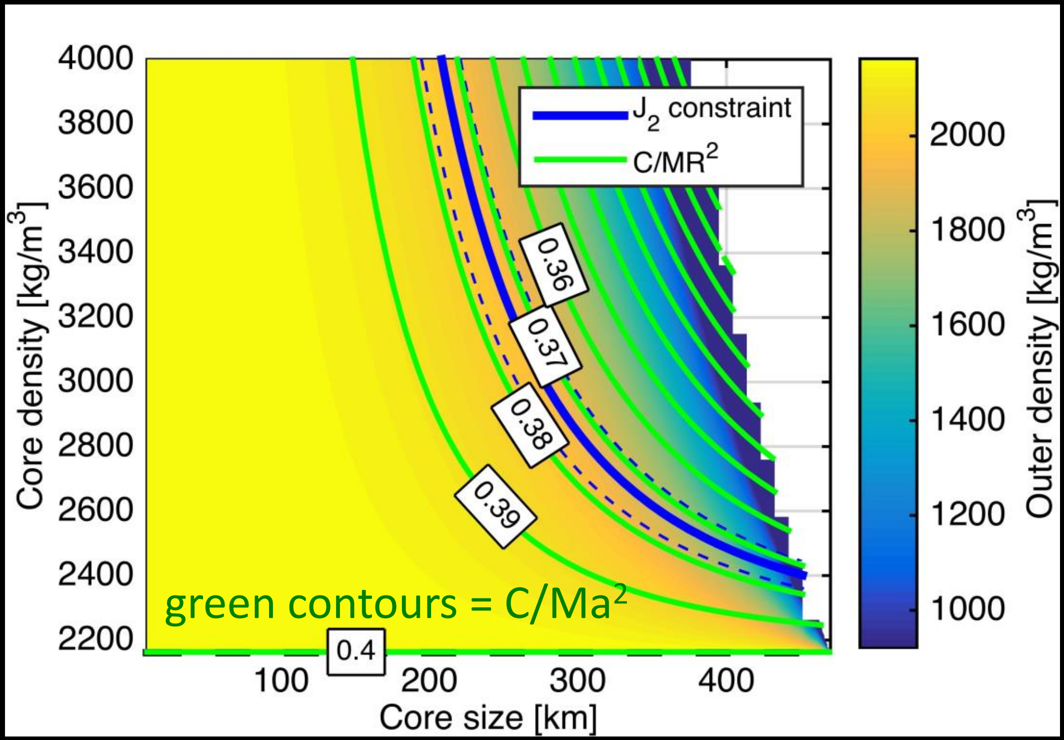


Backup slides



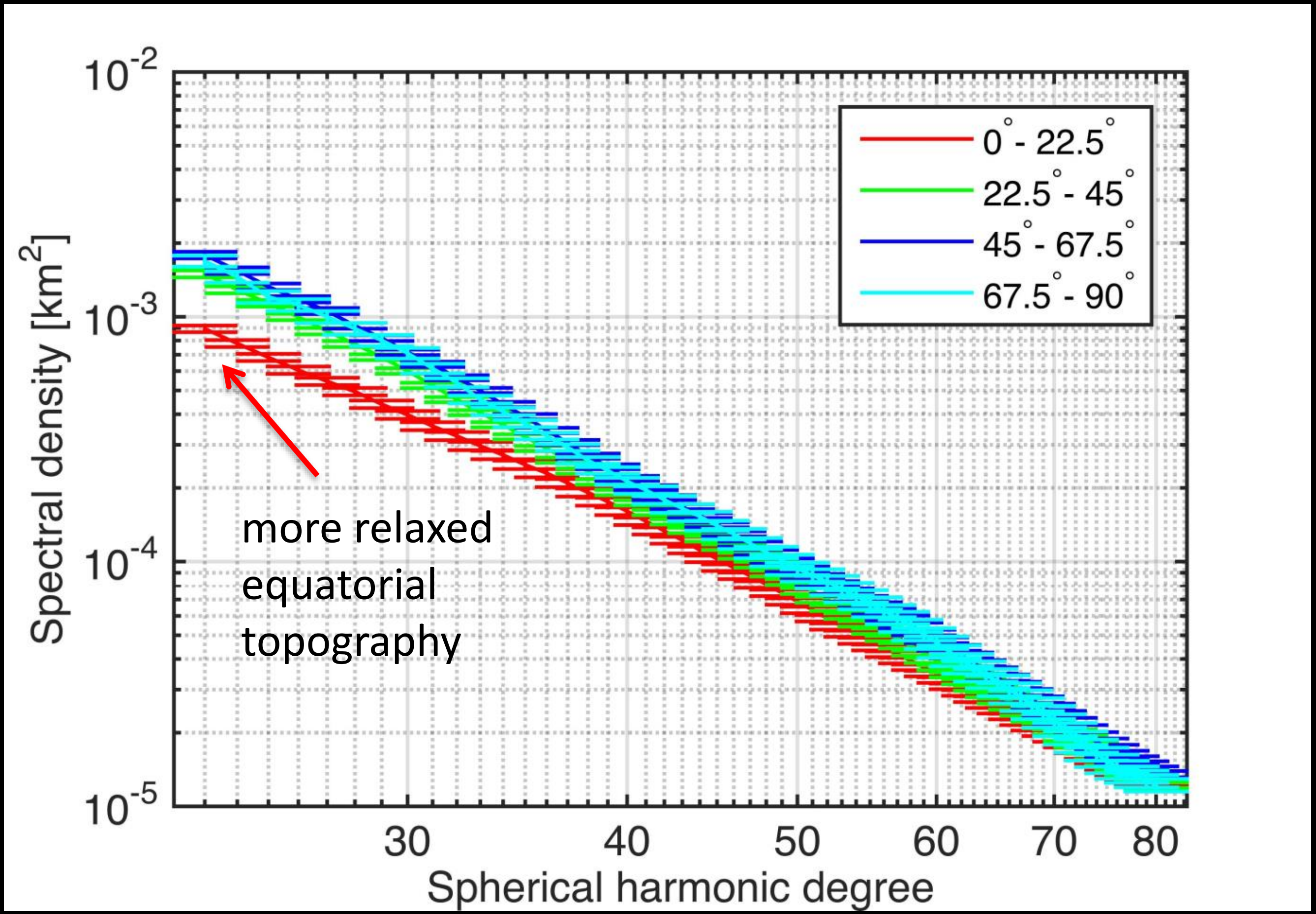
Two-layer model

- **Simplest model to interpret the gravity-topography data**
- **Only 5 parameters: two densities, two radii and rotation rate**
- **Yields $C/Ma^2 = 0.373$**
  $C/M(R_{vol})^2 = 0.392$



Using Tricarico 2014 for computing hydrostatic equilibrium

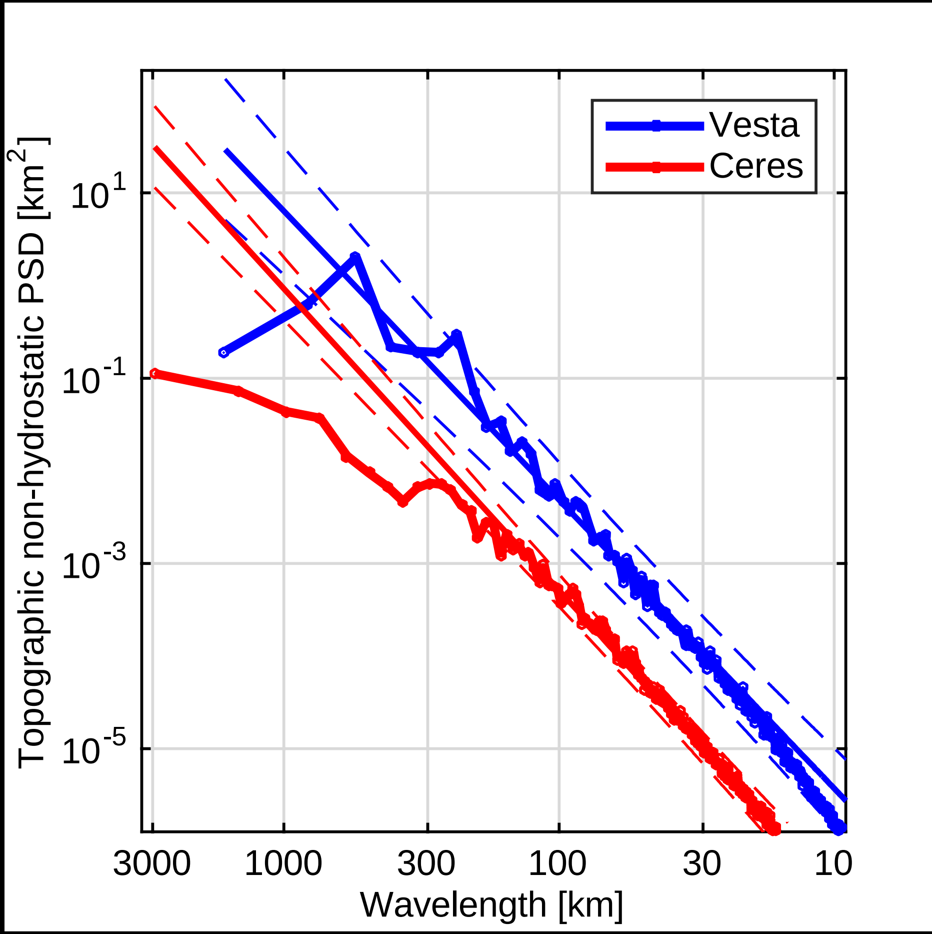
Latitude dependence of relaxation



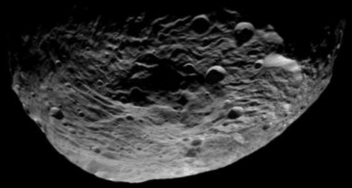
Ermakov et al., in prep

Evidence for viscous relaxation

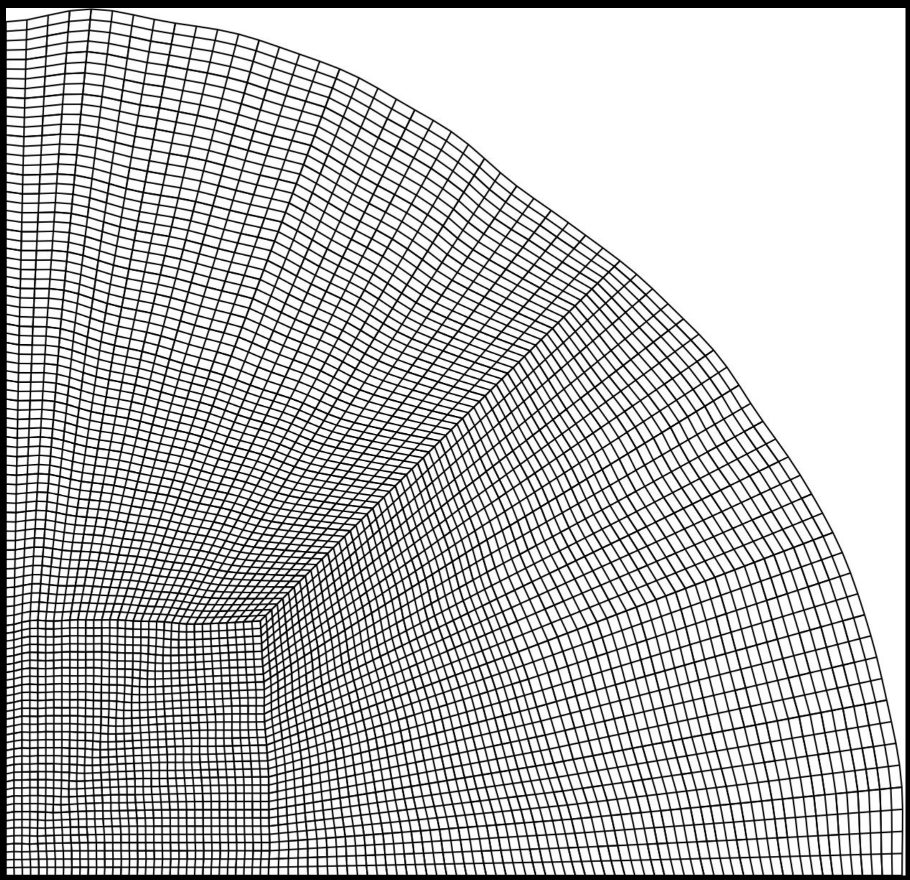
- **More general approach: study topography power spectrum**
- **Power spectra for Vesta closely fits with the power law to the lowest degrees (λ < 750 km)**
- **Ceres power spectrum deviates from the power law at λ > 270 km**



Ermakov et al,. in prep



Finite element model



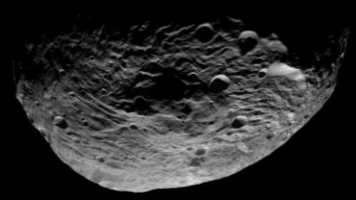
Fu et al., 2014; Fu et al, submitted to EPSL

- **Assume a density and rheology structure**
- **Solve Stokes equation for an incompressible flow using deal.ii library**

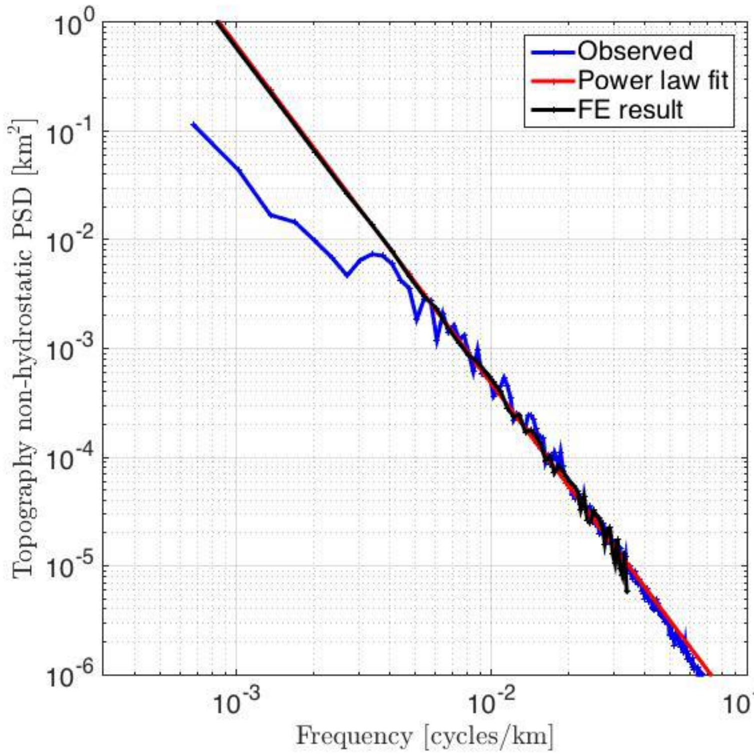
$$\partial_i(2\eta\dot{\varepsilon}_{ij}) - \partial_i p = -g_i\rho$$

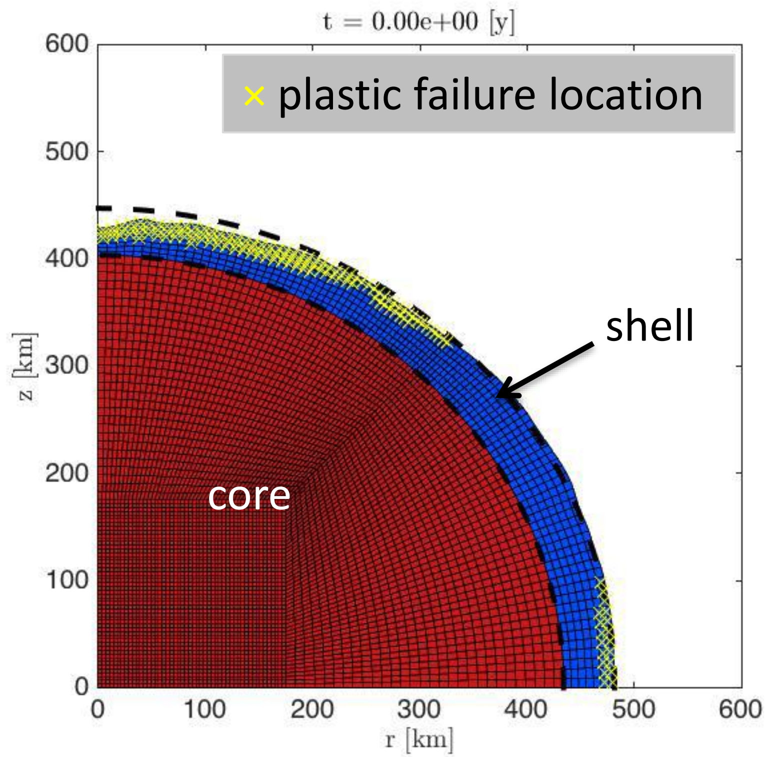
$$\P_i u_i = 0$$

- **Compute the evolution of the outer surface power spectrum**

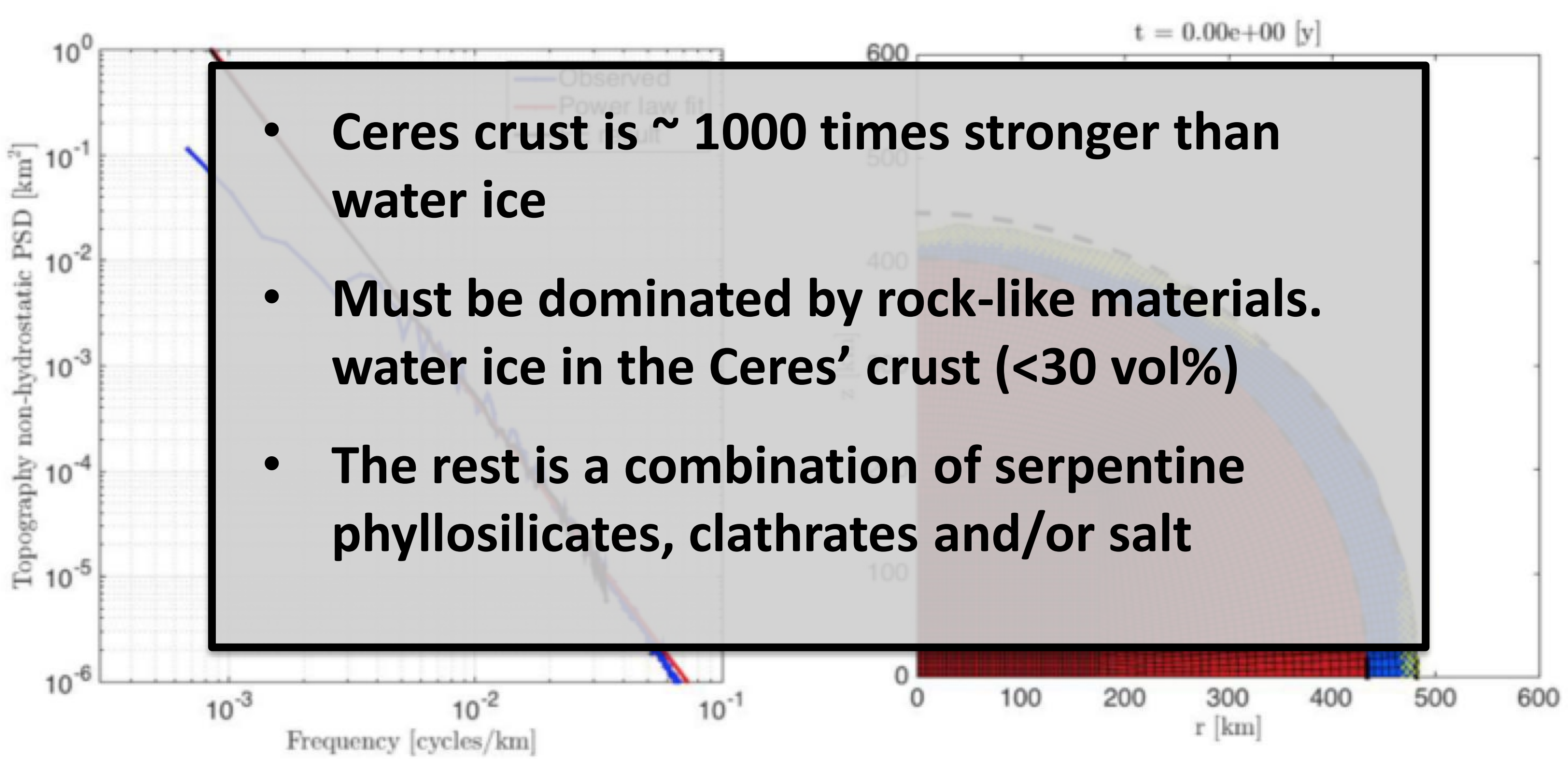


Example of a FE modeling run

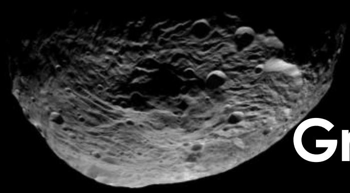




Finite element modeling results



- Ceres crust is ~ 1000 times stronger than water ice
- Must be dominated by rock-like materials. water ice in the Ceres' crust (<30 vol%)
- The rest is a combination of serpentine phyllosilicates, clathrates and/or salt



Gravity and topography in spherical harmonics

- **Shape radius vector**

$$r(\phi,\lambda)=R_0\left[\sum_{n=1}^{\infty}\sum_{m=0}^{n}\left(A_{nm}\cos(m\lambda)+B_{nm}\sin(m\lambda)\right)P_{nm}(\sin\phi)\right]$$

- **Gravitational potential**

$$U(r,\phi,\lambda)=\frac{GM}{R}\left[1+\sum_{n=2}^{\infty}\sum_{m=0}^{n}\left(\frac{R_0}{r}\right)^{n}\left(C_{nm}\cos(m\lambda)+S_{nm}\sin(m\lambda)\right)P_{nm}(\sin\phi)\right]$$

- **Power Spectral Density**

$$S_n^{gg}=\sum_{m=0}^{n}\frac{C_{nm}^2+S_{nm}^2}{2n+1}$$

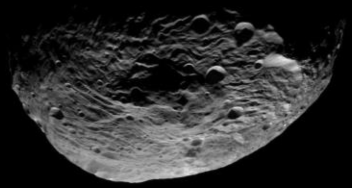
gravity

$$S_n^{tt}=\sum_{m=0}^{n}\frac{A_{nm}^2+B_{nm}^2}{2n+1}$$

topography

$$S_n^{gt}=\sum_{m=0}^{n}\frac{A_{nm}C_{nm}+B_{nm}S_{nm}}{2n+1}$$

gravity-topography cross power



Isostatic model

Z_n - gravity-topography admittance

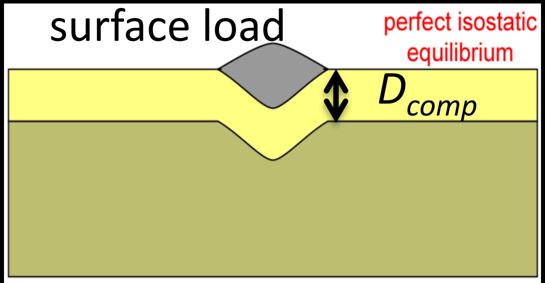
$$Z_n = \frac{S_{gt}}{S_{tt}}$$

- **Linear two-layer hydrostatic model**

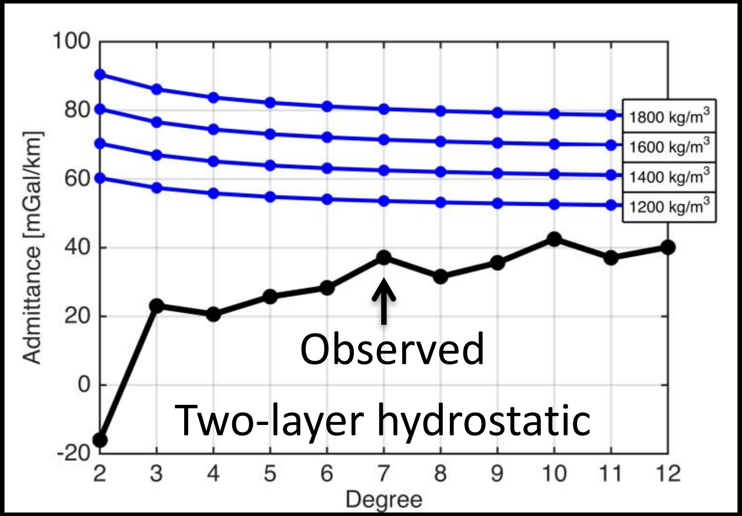
$$Z_n = \frac{GM}{R^3}\frac{3(n+1)}{2n+1}\frac{r_{crust}}{r_{mean}}$$

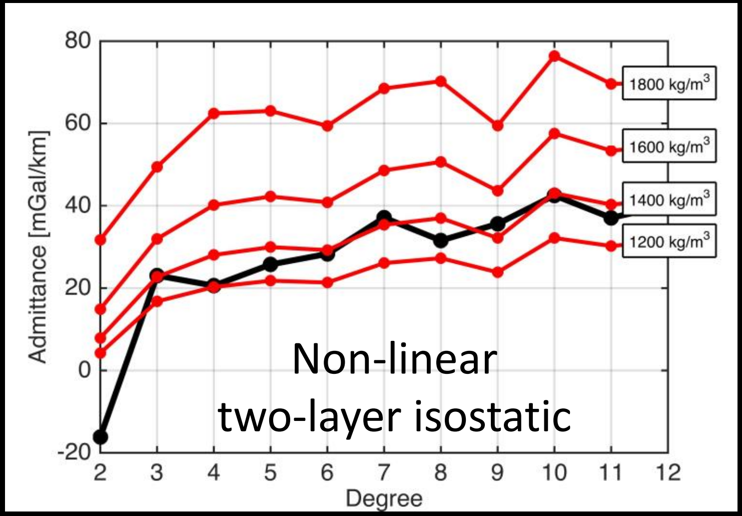
- **Linear isostatic model**

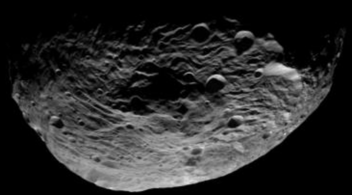
$$Z_n = \frac{GM}{R^3}\frac{3(n+1)}{2n+1}\frac{r_{crust}}{r_{mean}}\left[1-\left(1-\frac{D_{comp}}{R}\right)^{n}\right]$$



D_{comp}- depth of compensation

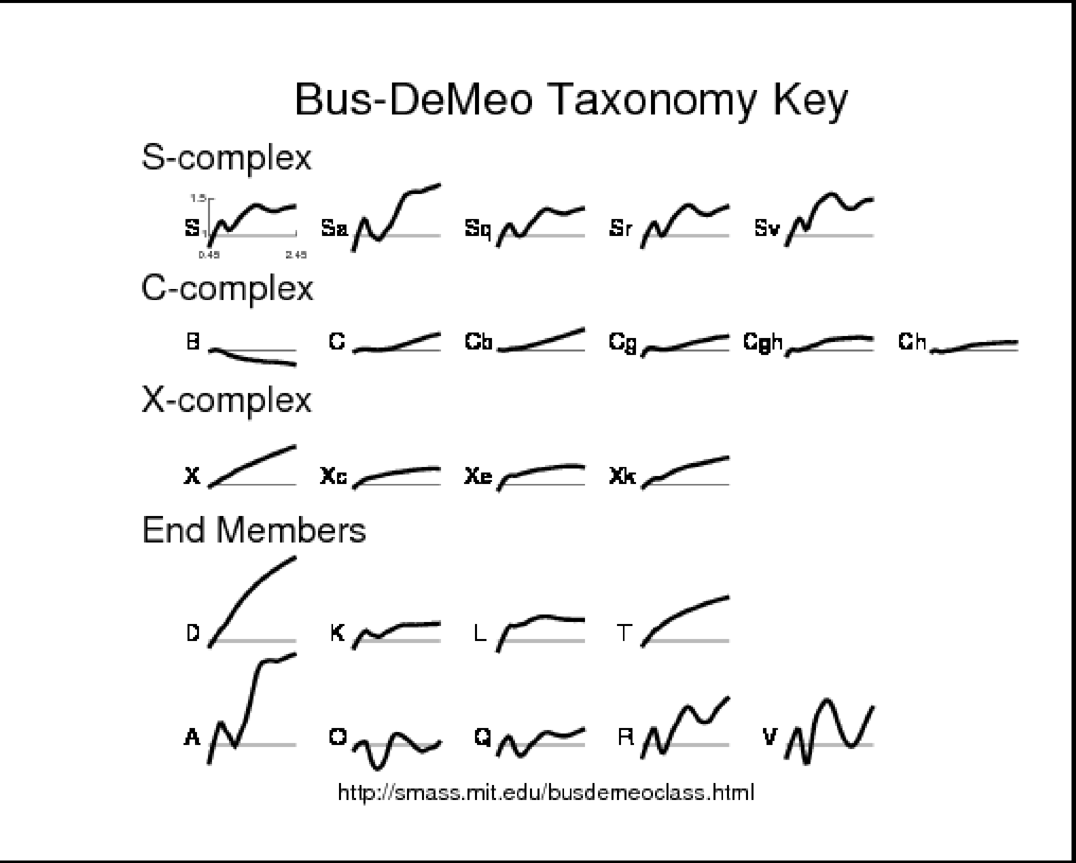


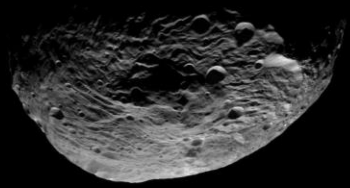




Why Vesta?

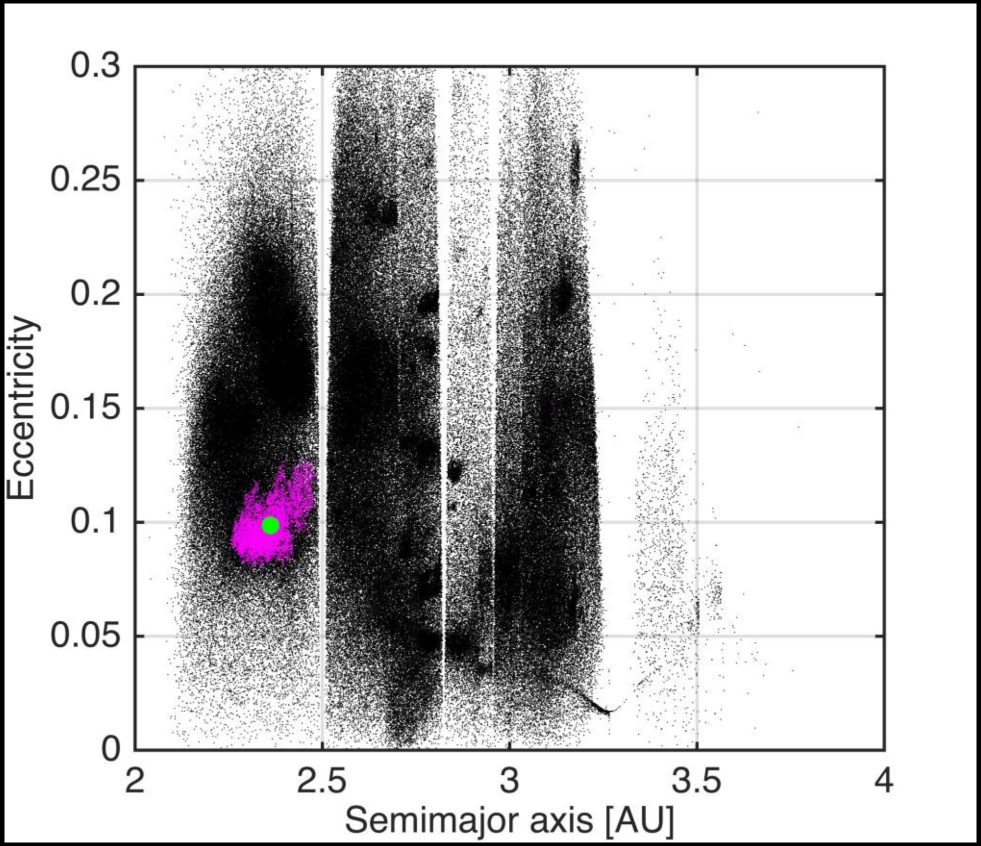
- **Unique basaltic spectrum**

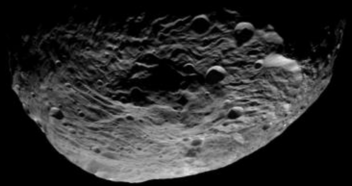




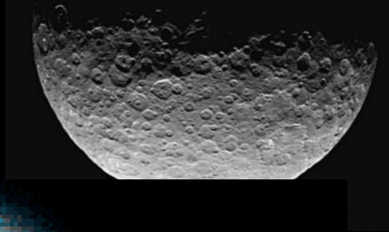
Why Vesta?

- **Unique basaltic spectrum**
- **A group of asteroids in the dynamical vicinity of Vesta with similar spectra**





Why Vesta?



- **Unique basaltic spectrum**
- **A group of asteroids in the dynamical vicinity of Vesta with similar spectra**
- **Large depression in the southern hemisphere of Vesta**

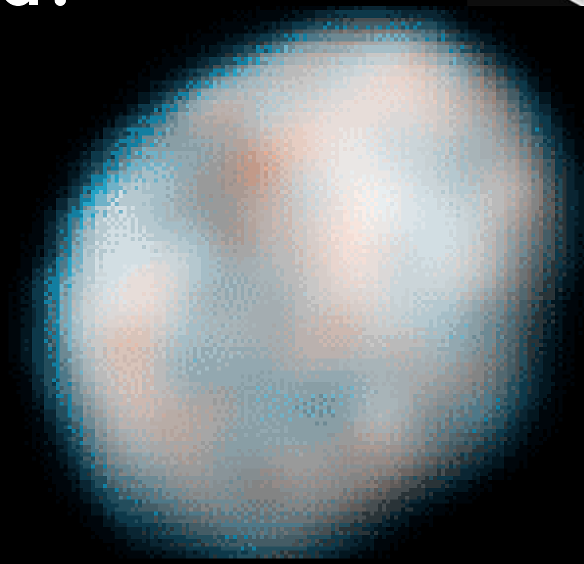
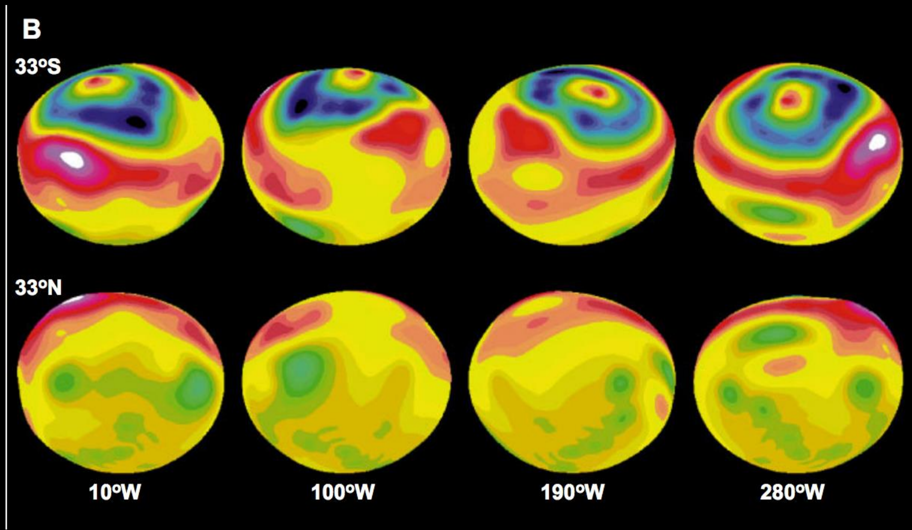
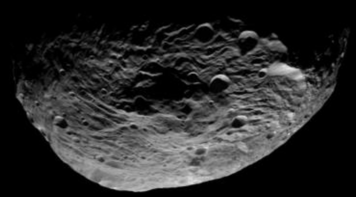


Image credit: NASA/HST

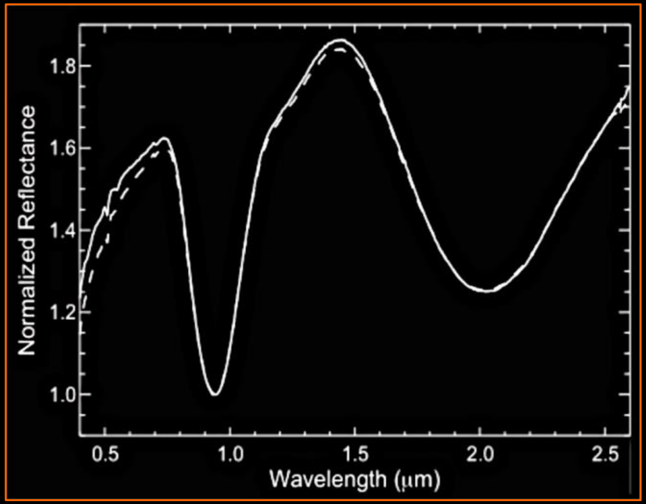


Thomas et al., 1997



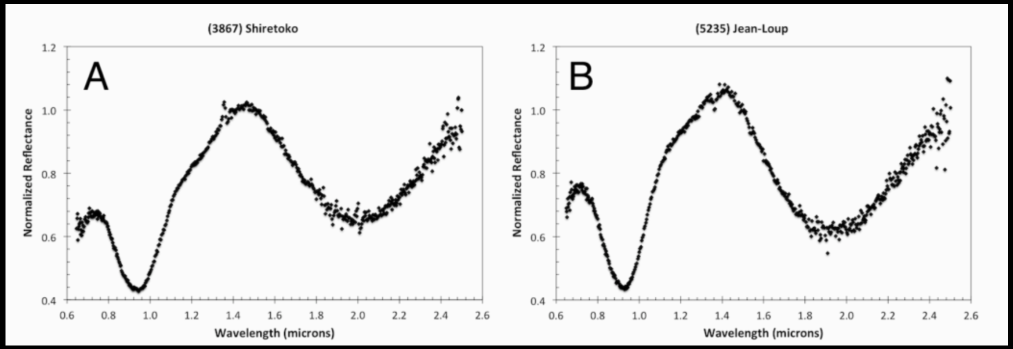
Why Vesta?

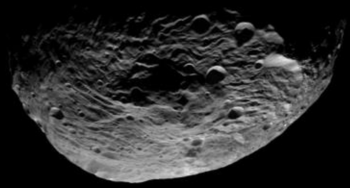
- **Unique basaltic spectrum**
- **A group of asteroids in the dynamical vicinity of Vesta with similar spectra**
- **Large depression in the southern hemisphere of Vesta**
- **A group of Howardite-Eucrite-Diogenite (HED) meteorites, with similar reflectance spectra**



↑ Reflectance spectra of eucrite Millbillillie from Wasson et al. (1998)

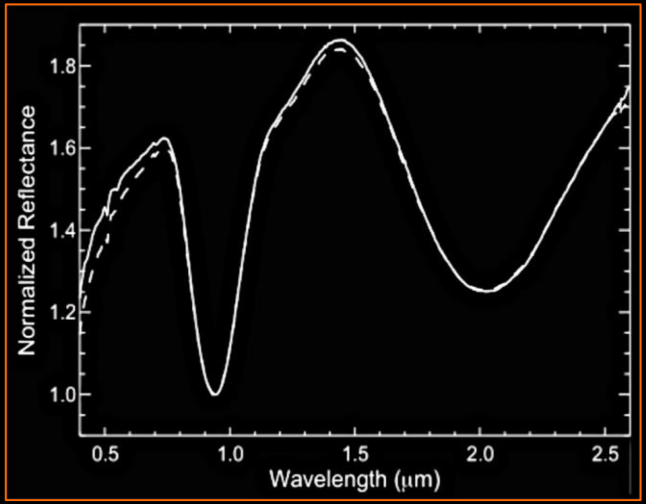
↓ V-type asteroids spectra from Hardensen et al., (2014)





Why Vesta?

- Unique basaltic spectrum
- A group of asteroids in the dynamical vicinity of Vesta with similar spectra
- Large depression in the southern hemisphere of Vesta
- A group of Howardite-Eucrite-Diogenite (HED) meteorites, with similar reflectance spectra
- Strongest connection between a class of meteorites and an asteroidal family



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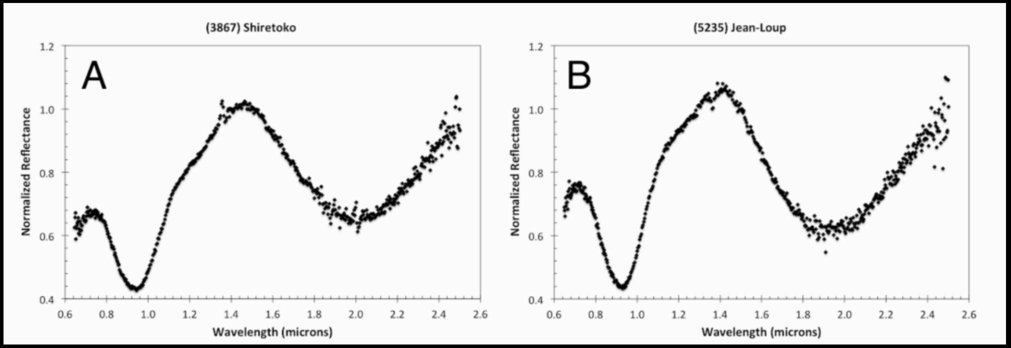
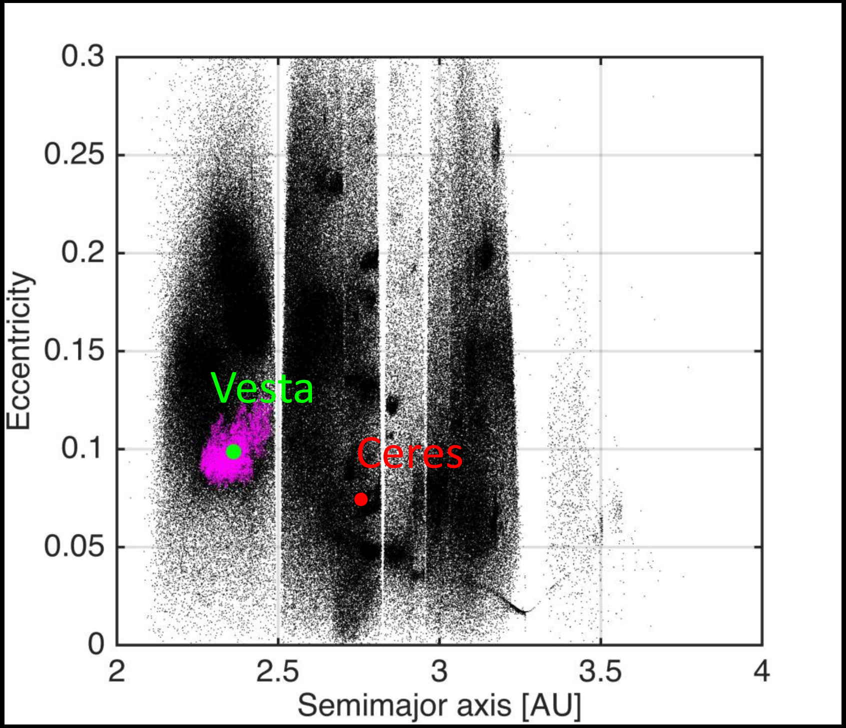
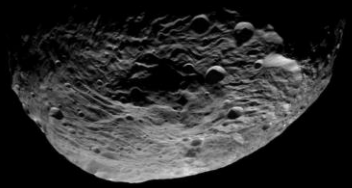


Why Ceres?

- Largest body in the asteroid belt
- Low density implies high volatile content
- Conditions for subsurface ocean
- Much easier to reach than other ocean worlds





What did we know before Dawn

- **Castillo-Rogez and McCord 2010**

  Ceres accreted as a mixture of ice and rock just a few My after the condensation of Calcium Aluminum-rich Inclusions (CAIs), and later differentiated into a water mantle and a mostly anhydrous silicate core.

- **Zolotov 2009**

  Ceres formed relatively late from planetesimals consisting of hydrated silicates.

- **Bland 2013**

  If Ceres *does* contain a water ice layer, its warm diurnally-averaged surface temperature ensures extensive viscous relaxation of even small impact craters especially near equator

Note on Vening-Meinesz and Kaula rules

- Vening-Meinesz rule for variance of topography (Vening-Meinesz, 1951)

  $V_t \sim 1/n^2$

- Kaula law for RMS of gravity (Kaula, 1963)

  $M_g \sim 1/n^2$

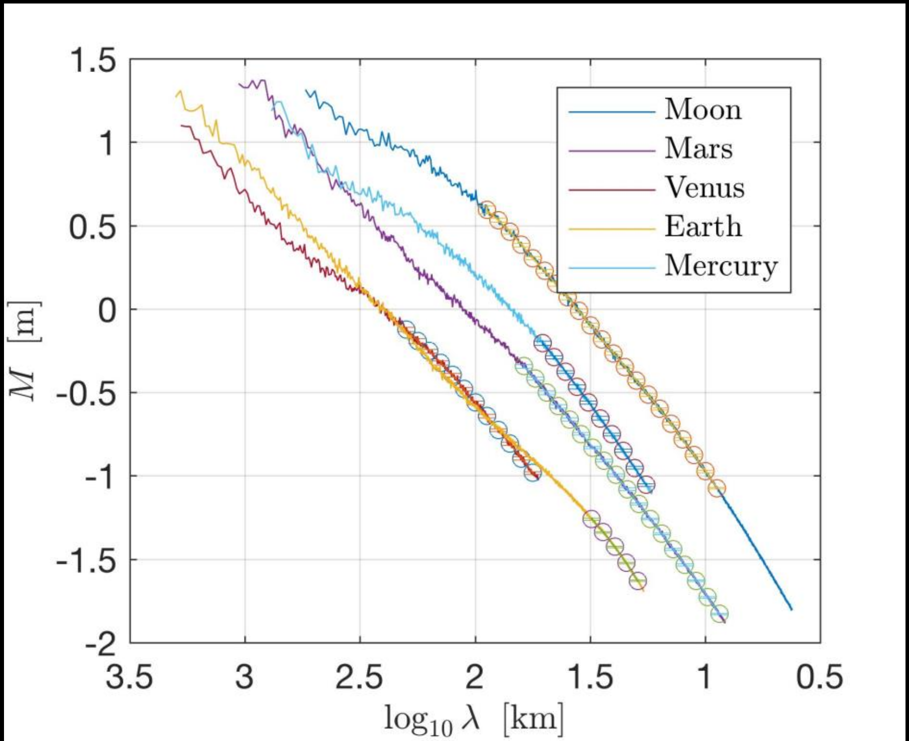
- Are these two rules consistent assuming uncompensated topography?

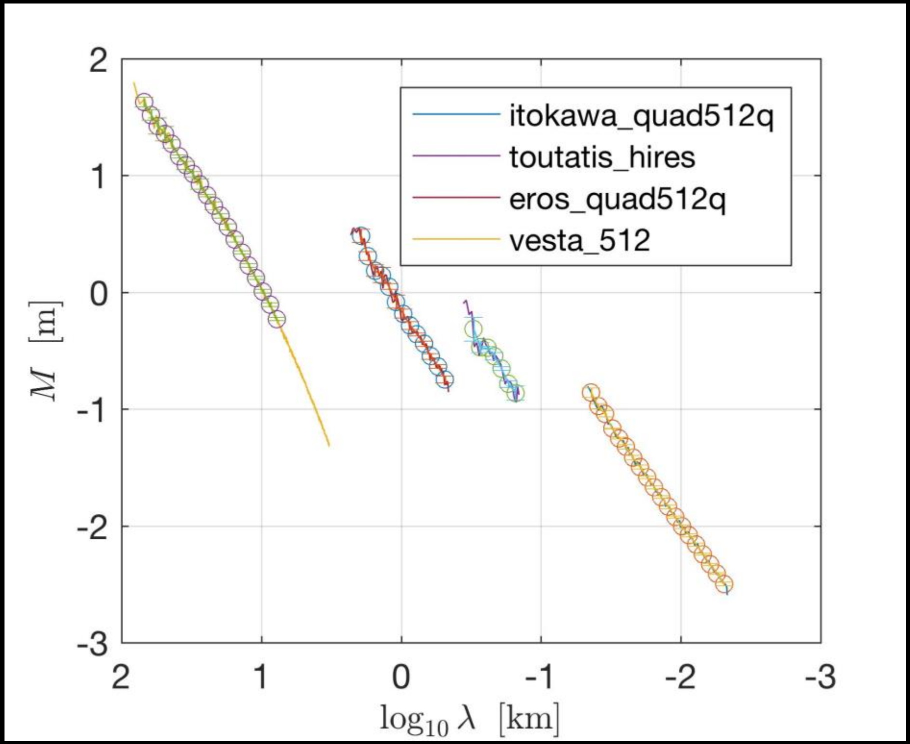
$V_t \sim 1/n^2 \Rightarrow M_t \sim 1/n^{1.5} \Rightarrow M_g \sim 1/n^{2.5}$

- But Kaula rule says $M_g \sim 1/n^2$ NOT $M_g \sim 1/n^{2.5}$

- Typically assumed in the literature Kaula and Vening-Meinesz rules are not mutually consistent assuming uncompensated topography

RMS spectra


Moon
Mars
Venus
Earth
Mercury
M [m]
$\log_{10} \lambda$ [km]


itokawa_quad512q
toutatis_hires
eros_quad512q
vesta_512
M [m]
$\log_{10} \lambda$ [km]

Power laws

- **General form of a power law**

$$M = AR^{\alpha_1}\varrho^{\alpha_2}\lambda^{\alpha_3}$$

- **Power law assuming (inverse) surface gravity scaling (g ~ $R*\rho$)**

$$M = AR^{-1}\varrho^{-1}\lambda^{\alpha_3}$$

- **If we take a $\log_{10}$ of M, we get an equation of a hyperplane**

$$\log_{10}M = \log_{10}A + \alpha_1\log_{10}R + \alpha_2\log_{10}\varrho + \alpha_3\log_{10}\lambda$$

- **In our data set, we have a lot of points along the λ direction and not as many points on the other two (R and ρ) directions.**
  - **In the R and ρ directions, we have as many data points as we have bodies**
  - **In the λ direction, we have as many data points as many we have λ bins.**

Markov-chain Monte-Carlo (MCMC)

- **We use a free Python library `emcee` (Foreman-Mackey et al., 2013) to find the best-fit parameters of a power law.**

- **`emcee` library is based on *Affine Invariant Markov chain Monte Carlo sampler* (Goodman and Weare, 2010)**

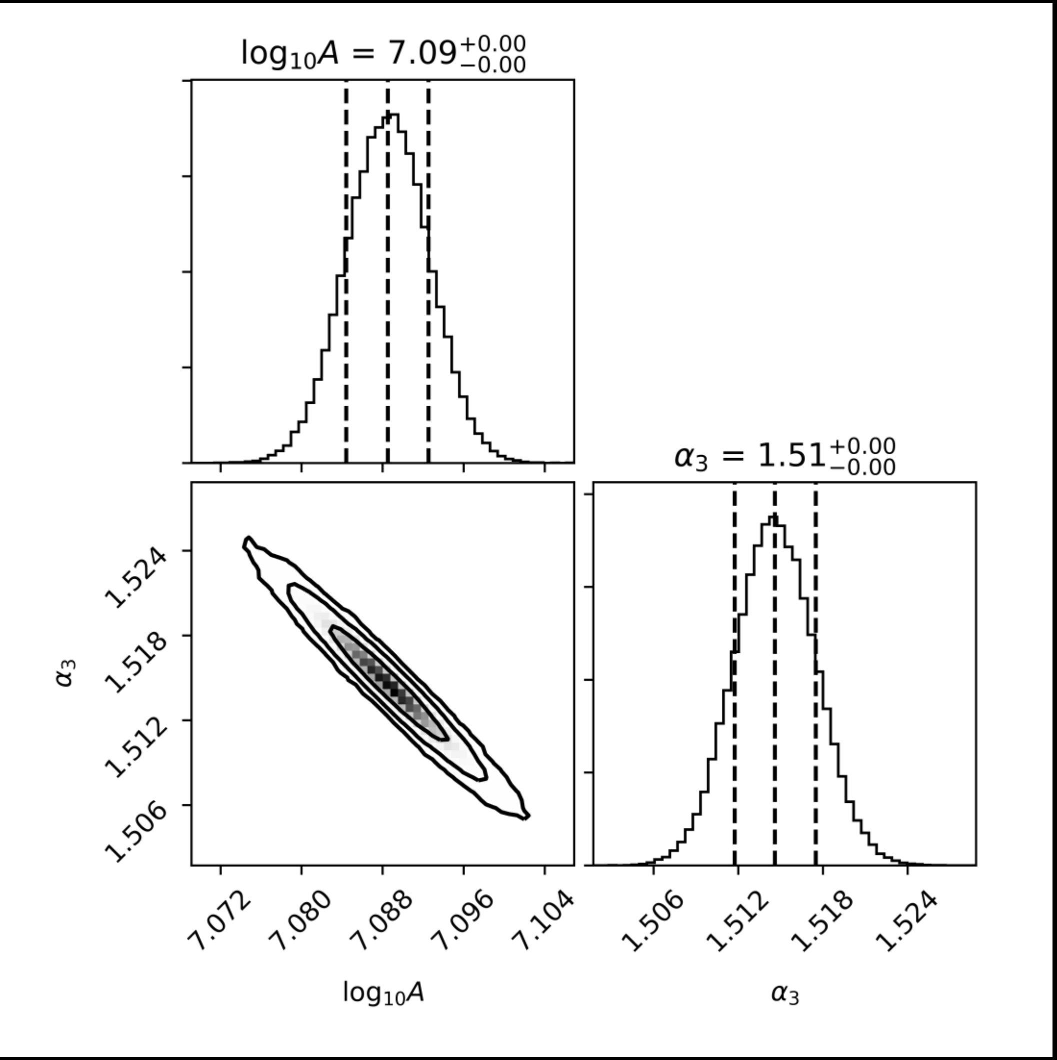
- **We fit a power law model with:**
  - **two parameters: *A*, α_3 -- assuming surface gravity scaling (α_1=-1, α_2=-1)**
  - **four parameters: *A*, α_1, α_2, α_3 -- general scaling.**

- **For each MCMC run, we will show:**
  - **A triangle plot of the posterior distribution of the model parameters. This allows seeing the covariances between the parameters.**
  - **A plot of best-fit model versus the observations. We also show a reduced chi squared value to judge about the quality of the best-fit.**

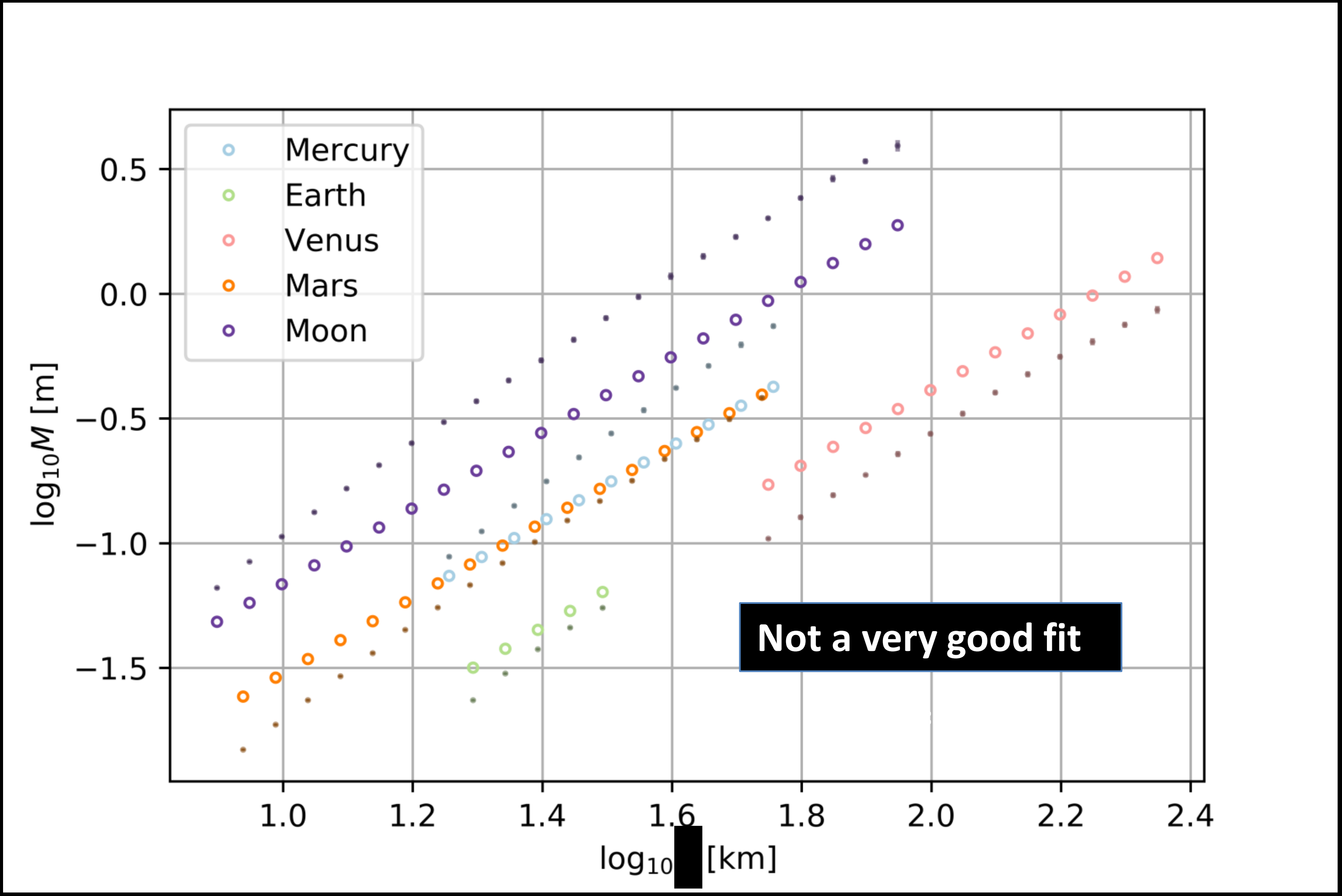
- **emcee is an extensible, pure-Python implementation of**

Results of the MCMC runs

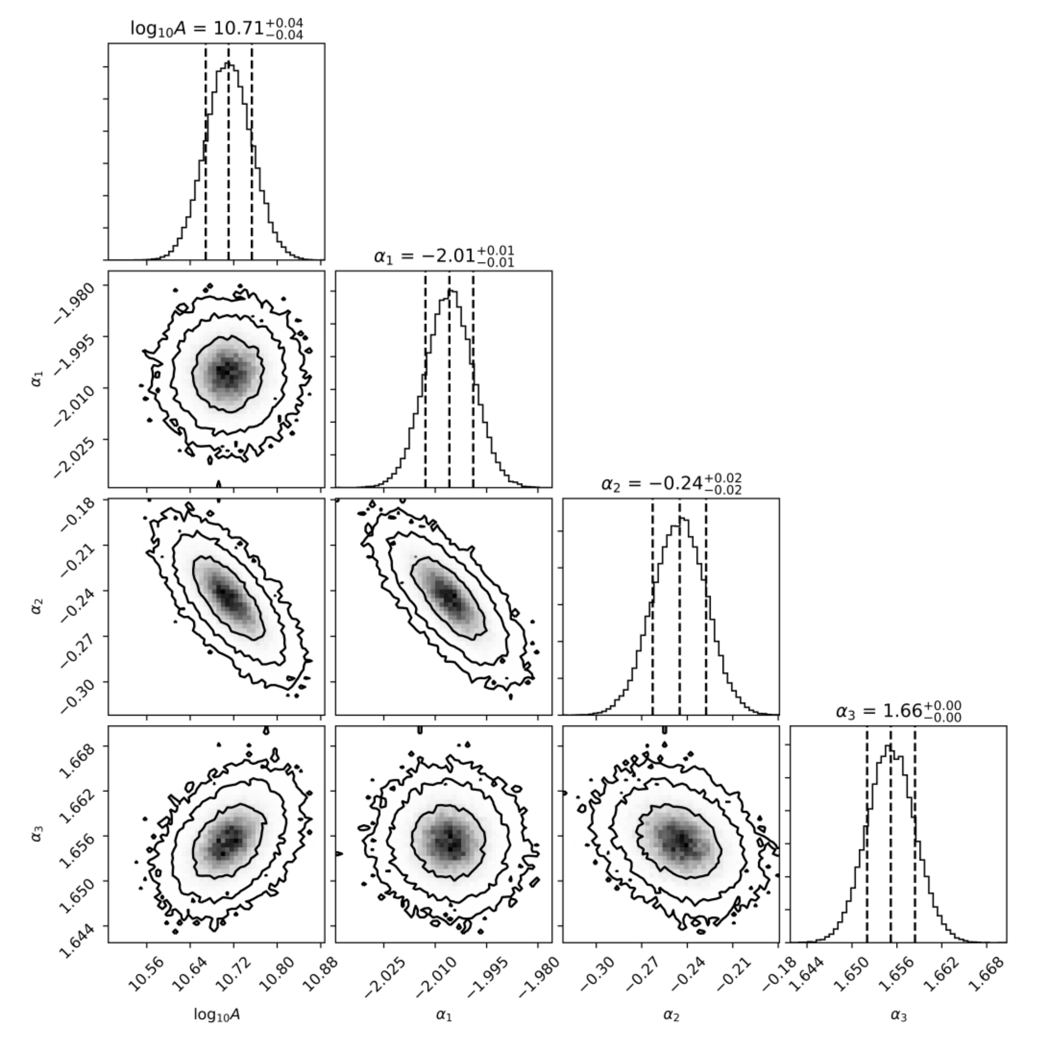
Planets, gravity scaling



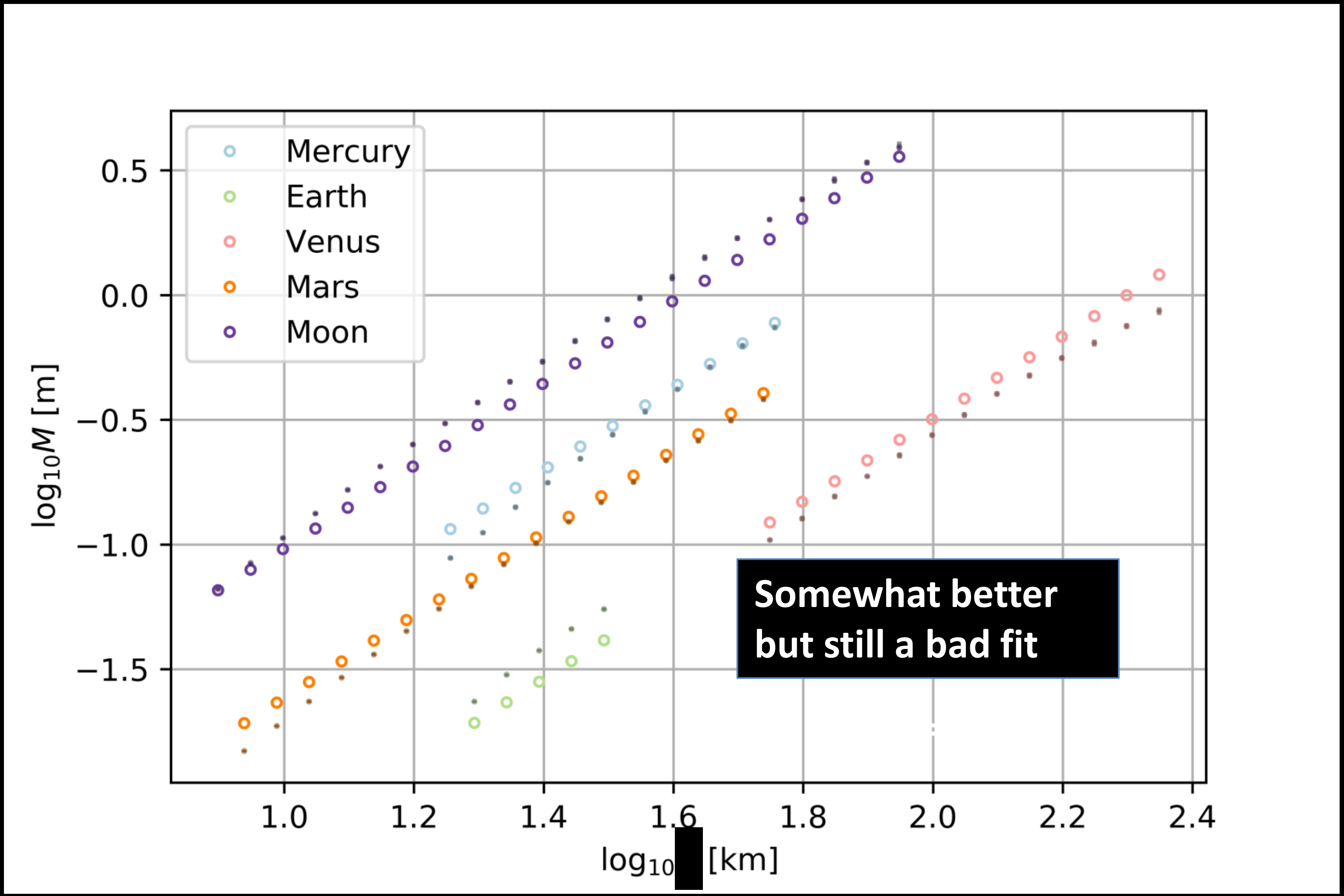
Planets, gravity scaling



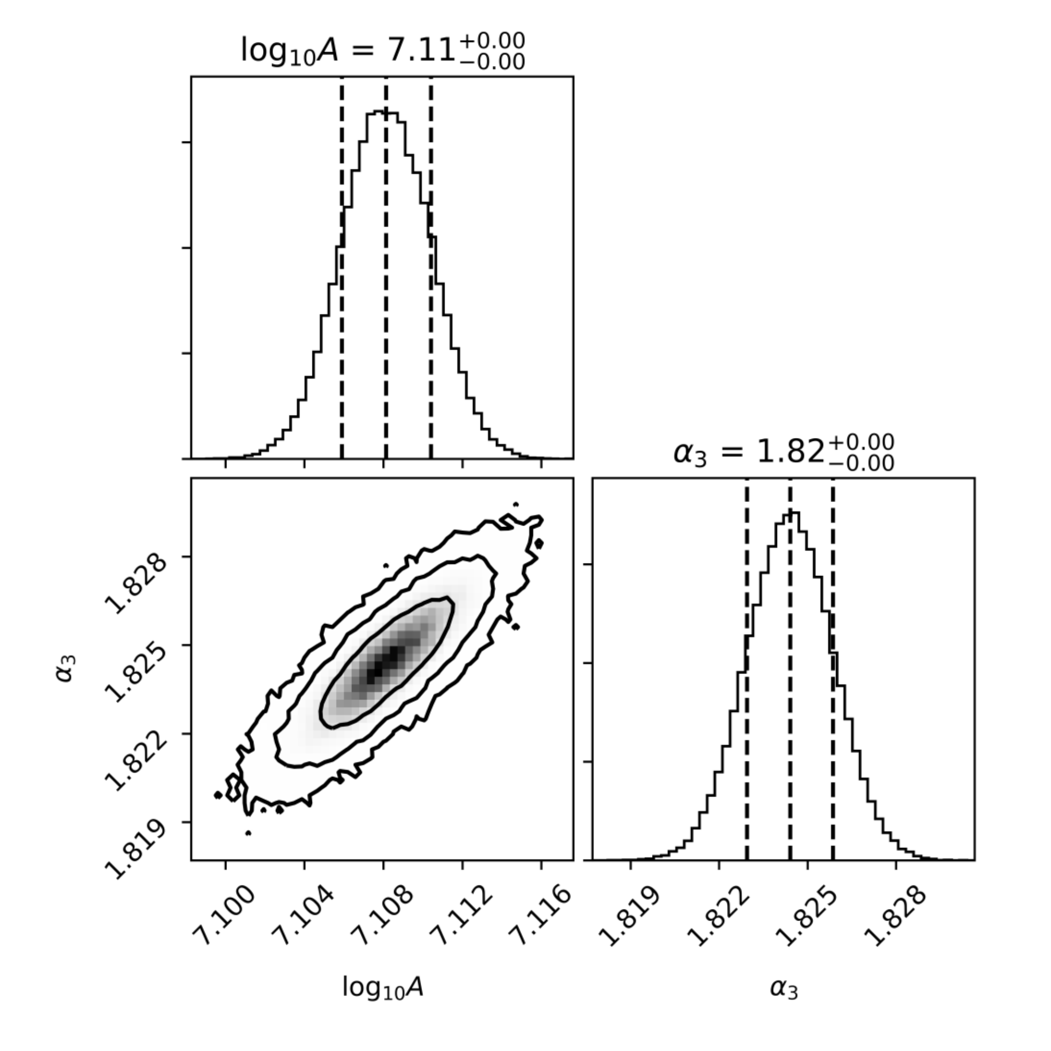
Planets, general scaling



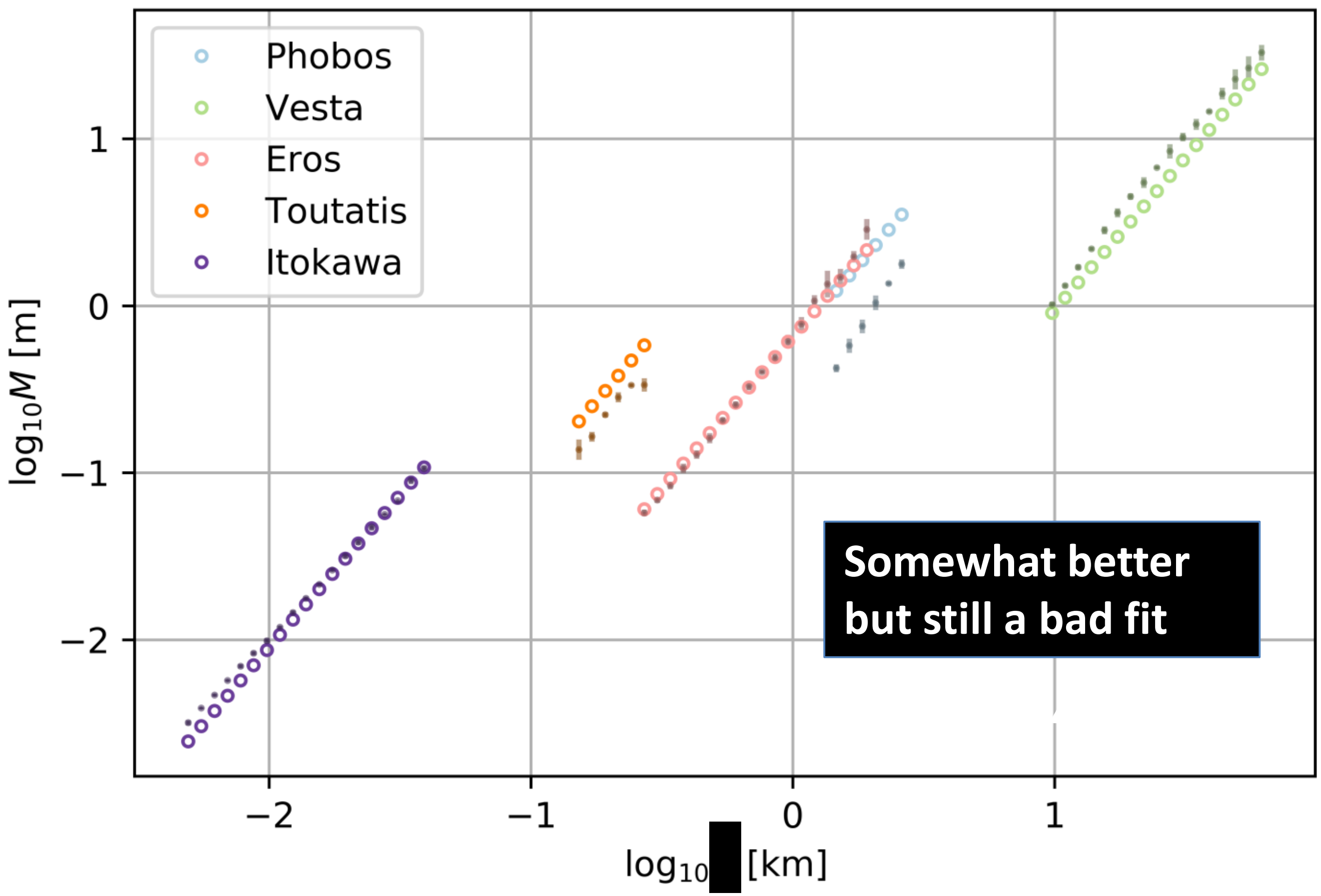
Planets, general scaling



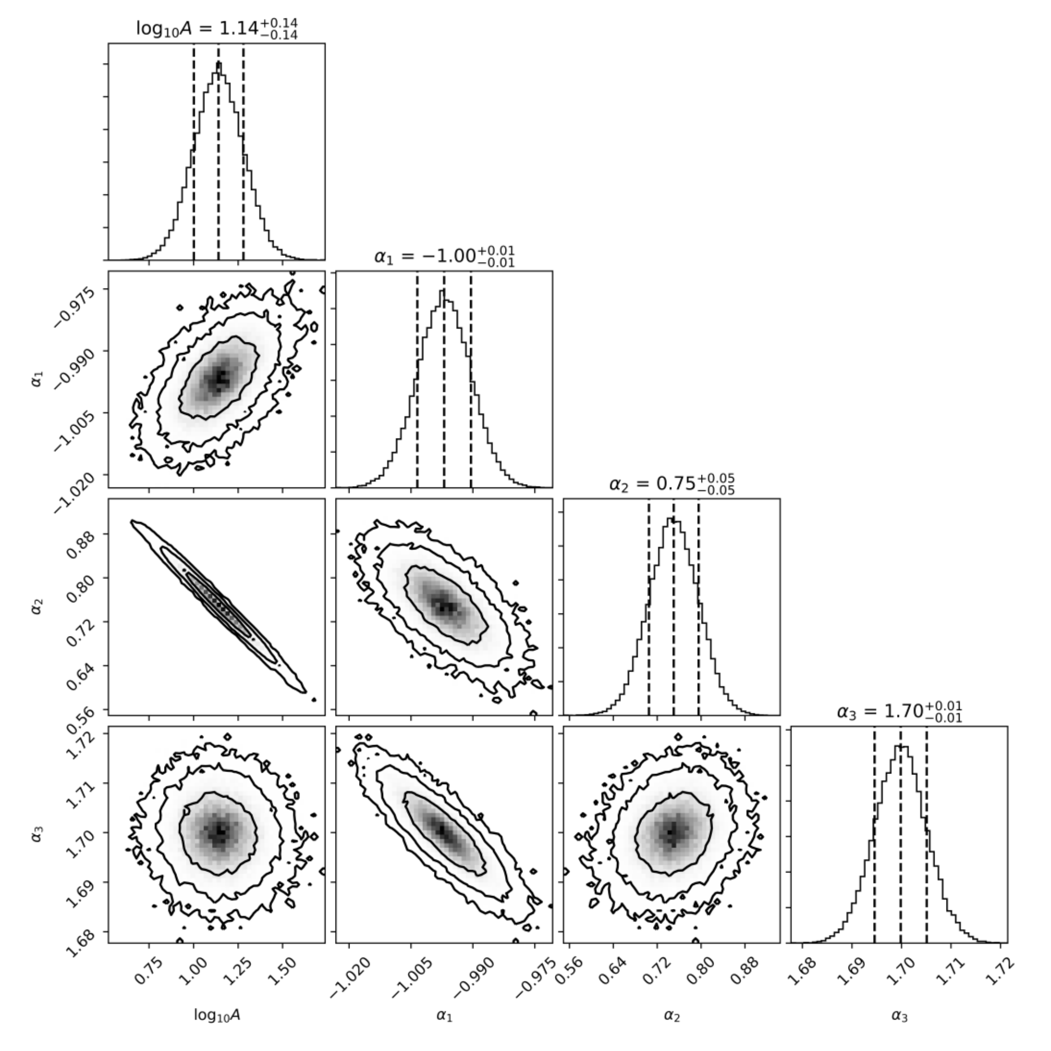
Asteroids, gravity scaling



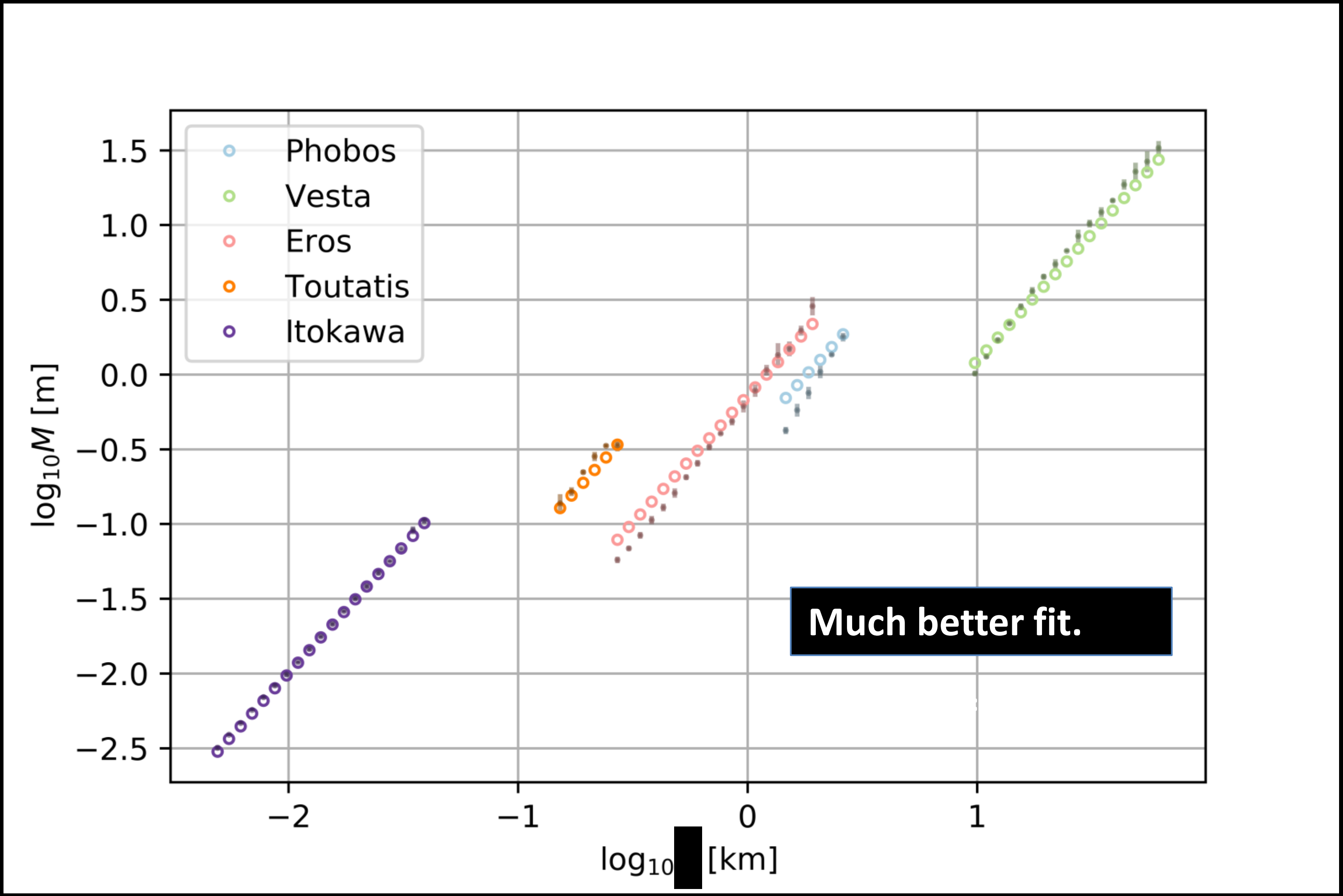
Asteroids, gravity scaling



Asteroids, general scaling



Asteroids, general scaling



A priori constraint on gravity RMS

Choose R and ρ

Given R and ρ and a range of λ, sample multivariate normal distribution to get A, $\alpha_1, \alpha_2, \alpha_3$

Find the upper and lower bounds on the gravity RMS spectum

Given A, $\alpha_1, \alpha_2, \alpha_3$, compute topography RMS spectrum

Given topography RMS spectrum, generate SH coefficients that follow the chosen spectrum

Compute gravity-from-topography using Wieczorek & Phillips 1998 until convergence w.r.t. to the power of topography

Summary

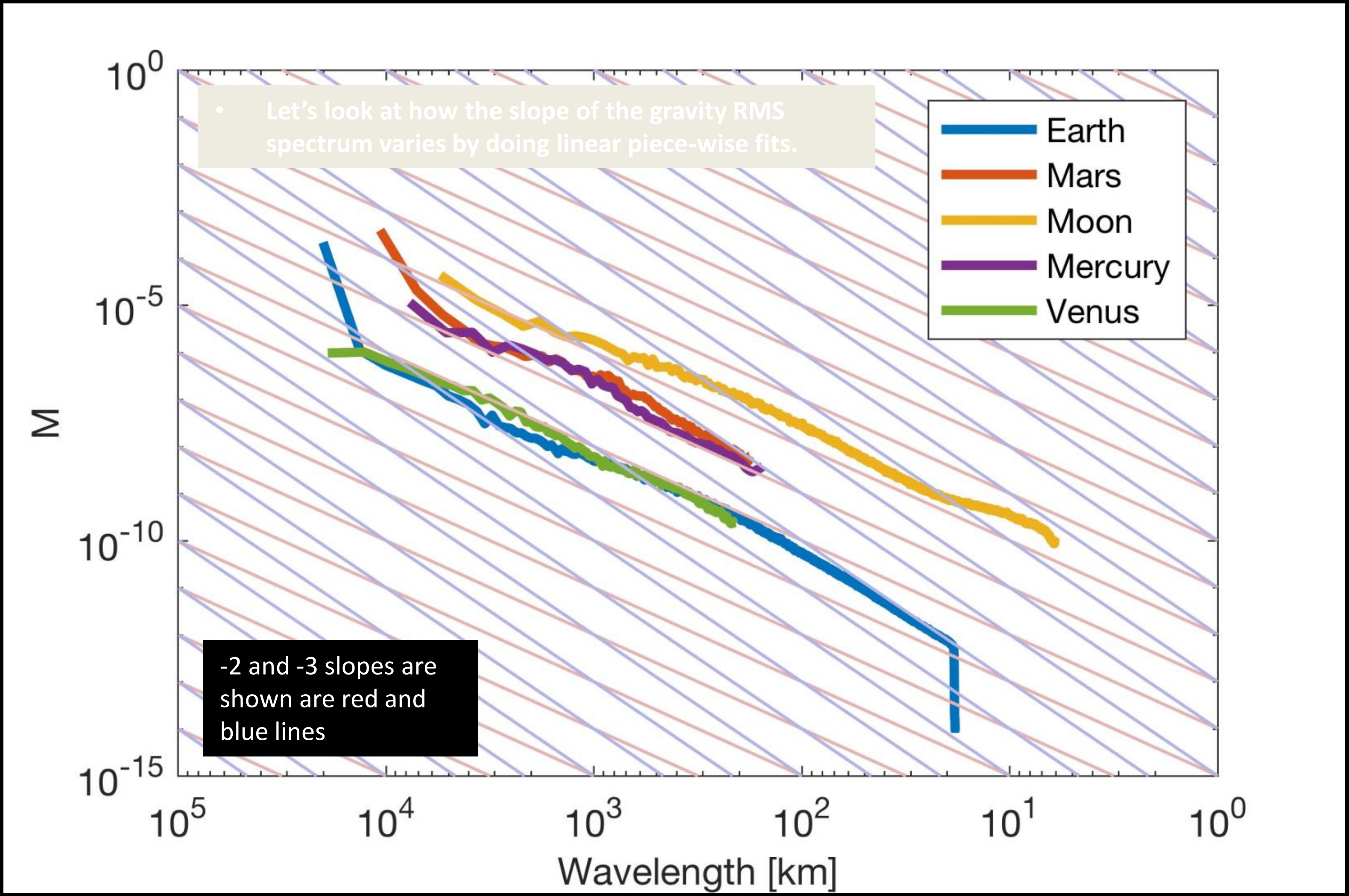
- Topography RMS spectra of 4 terrestrial planets and the Moon cannot be simultaneously fit with a single power law of the gravity-scaling or general form.

- Topography RMS spectra of asteroids CANNOT be *satisfactorily* fit with a power law the gravity-scaling form.

- Topography RMS spectra of asteroids CAN be *satisfactorily* fit with a power law of the general form.

- Despite having different internal structure, composition and mechanical properties of the surface layer, the asteroid topography spectra can be effectively modeled as a general power law

Gravity RMS spectra



Slopes of piecewise fitted gravity RMS spectra